ENERGY SYSTEMS
&
APPLICATIONS

https://esajournal.com

Research paper

Influence of Zeolite Y Loading on Product Distribution and GC-MS Characterization of Bio-oil from Achyranthes aspera Wood Residue Pyrolysis

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

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

Article information:
Received: 23/12/2025, Revision: 21/03/2026, Accepted: 28/03/2026.
DOI: https://doi.org/10.5281/zenodo.20942988

ABSTRACT

Biomass-derived bio-oil is a promising renewable alternative to fossil fuels; however, its high oxygen content, chemical instability, and acidity severely limit direct utilization. This study presents the first systematic investigation of the catalytic pyrolysis of *Achyranthes aspera* wood residue; an abundant yet underutilized lignocellulosic biomass in Nigeria using zeolite Y catalyst to improve bio-oil quality at the molecular level. Pyrolysis experiments were conducted at 500 °C under an inert nitrogen atmosphere across four biomass-to-catalyst ratios: 100/0, 95/5, 90/10, and 85/15 (wt.%). Product yield analysis demonstrated that increasing zeolite Y loading induced a systematic carbon redistribution from the liquid to the gas phase: bio-oil yield declined from 52.95 wt.% (95/5) to 29.45 wt.% (85/15), while syngas yield rose proportionally from 22.40 wt.% to 53.50 wt.%, and biochar yield decreased from 25.75 wt.% to 17.05 wt.%. GC-MS characterization revealed substantial molecular transformation of the bio-oil: phenolic compounds increased from 19.95% (non-catalytic) to 33.08% (85/15), representing a 65.8% enhancement, while carboxylic acids decreased from 5.28% to 4.19%, a 20.64% reduction. ANOVA ($p < 0.05$) confirmed that catalyst loading significantly influenced both product distribution and bio-oil molecular composition. Mean-based linear interpolation of the product yield data identified the optimal catalytic loading range as 10–15 wt.% zeolite Y (biomass-to-catalyst ratio 90/10 to 85/15), with a precisely interpolated optimal value of 10.43 wt.% at which bio-oil yield equals its experimental mean of 45.25 wt.%. The 90/10 ratio represents the nearest experimentally tested approximation to this analytically derived optimum, delivering a balanced output of 46.75 wt.% bio-oil, 21.30 wt.% biochar, and 31.95 wt.% syngas. GC-MS quantification is acknowledged as semi-quantitative, and compositional findings are interpreted as indicative trends pending comprehensive physicochemical characterization. These findings establish *A. aspera* as a viable pyrolysis feedstock and demonstrate that zeolite Y effectively tailors bio-oil composition for fuel, resin, pharmaceutical, and specialty chemical applications.

Keywords: *Achyranthes aspera, Bio-oil, Catalytic pyrolysis, Zeolite Y, Phenolic enrichment, GC-MS characterization.*

Cite as: Oyebanji, J. A., Osanyinpeju, K. L., Adetunji, A. C., Oyedepo, S. O., Adetokunbo, I. A., & Olalekan, O. O. (2026). Influence of zeolite Y loading on product distribution and GC-MS characterization of bio-oil from achyranthes aspera wood residue pyrolysis. Energy Systems & Applications, 1(1): 55-81.

I. INTRODUCTİON

The depletion of fossil fuel reserves, escalating environmental pollution, and global climate change have intensified the search for renewable and sustainable energy alternatives (Oyebanji et al., 2018a; Osanyinpeju et al., 2018a; Osanyinpeju et al., 2018b; Jaiswal et al., 2022). Biomass, an abundant and carbon-neutral resource, has gained significant attention for its ability to be converted into fuels and valuable chemicals through thermochemical processes (Tursi A., 2019; Shahbaz et al., 2021; Ngugen and Le, 2023; Begum et al., 2024). Among these, pyrolysis stands out as an efficient pathway for transforming lignocellulosic residues into three primary products: bio-oil, biochar, and syngas (Yogalakshmi et al., 2022; Oyebanji et al., 2023a; Ameh et al., 2024; Mignogna et al., 2024).

Bio-oil, the liquid fraction of pyrolysis, is particularly attractive as a potential substitute for petroleum-derived fuels and as a source of high-value chemicals (Ilyin and Makarova, 2022; Egbosiuba, 2022). However, its direct utilization is limited due to its high oxygen content, chemical instability, and acidity (Sanchez-Borrego et al., 2021; Lachos-Perez et al., 2023). These properties arise from the presence of hundreds of oxygenated organic compounds, including phenols, ketones, aldehydes, carboxylic acids, and furans (Dai et al., 2020; Castro et al., 2021; Lin et al., 2022). Such compositional complexity adversely affects the physicochemical characteristics of bio-oil, including viscosity, storage stability, heating value, and compatibility with conventional fuel systems (Oyebanji et al., 2020; Kass et al., 2020; Nanda et al., 2021; Stelmach et al., 2023; Liaqat et al., 2024).

In comparison with syngas and biochar, bio-oil offers a higher volumetric energy density, making it easier to store, handle, and transport (Oyebanji et al., 2018b; Zheng et al., 2022; El-Araby, 2024). With appropriate catalytic upgrading or hydro-processing, it can be refined into transportation fuels or used as a feedstock for the production of chemicals such as phenols and aromatics (Kumar and Strezov, 2021; Bampaoucet et al., 2022; Diaz et al., 2024). Syngas, consisting primarily of H_2, CO, and light hydrocarbons, serves as a versatile intermediate for heat and power generation or for conversion into liquid fuels via Fischer–Tropsch synthesis (Rey et al., 2024; Khlifi et al., 2024; Motta et al. 2025; Yilbasi, 2025). Biochar, a solid carbon-rich residue, enhances soil fertility, sequesters carbon, and can serve as a precursor for activated carbon or as a catalyst support (Li and Tasnady, 2023; Ganesapillai et al., 2023; Yadav et al., 2023; Shoudho et al., 2024; Mahmud et al., 2025).

Despite its potential, bio-oil suffers from instability and compositional variability, which hinder large-scale deployment (Chen et al., 2020; Machado et al., 2022). A detailed understanding of its chemical speciation and molecular composition is therefore essential for optimizing pyrolysis conditions, improving product quality, and developing efficient upgrading strategies. While proximate and ultimate analyses provide general information on bulk composition, they fail to identify specific molecular species responsible for instability and poor performance. Techniques such as Gas Chromatography–Mass Spectrometry (GC–MS) offer critical insight into the molecular structure and functional groups present, enabling a clearer understanding of reaction mechanisms and fuel properties (Oyebanji et al., 2018a; Oyebanji et al.,2018b; Oyebanji et al., 2020; Oyebanji et al., 2021).

Achyranthes aspera wood residue represents a promising but underutilized lignocellulosic biomass resource. Its abundance, structural characteristics, and favorable phytochemical composition make it suitable for thermochemical conversion. However, information on the chemical composition and molecular profile of bio-oil derived from this biomass is scarce. Bridging this knowledge gap is crucial for assessing its potential as a renewable feedstock and for identifying routes to enhance the quality and stability of its bio-oil. Despite the abundance of Achyranthes aspera wood residue in Nigeria and similar regions, its potential as a pyrolysis feedstock remains unexplored. Conventional pyrolysis produces bio-oil with high oxygen content (35-40%), causing instability, corrosivity, and low heating value. While zeolite catalysts have shown promise in upgrading bio-oils from various feedstocks, systematic investigation of zeolite Y loading effects on Achyranthes aspera pyrolysis products is lacking. Specifically, the relationship between catalyst proportion and phenolic enrichment requires quantification to optimize bio-oil quality for potential applications (Oyebanji et al., 2020; Oyebanji et al., 2021; Oyebanji et al., 2023b).

II. MATERIAL AND METHOD

This section presents the materials, experimental procedures, and analytical techniques employed in this study. The methodology was designed to investigate the effect of zeolite Y catalyst on the pyrolysis behavior of Achyranthes aspera wood residue and to determine the chemical speciation and molecular composition of the resulting bio-oils. The experimental process involved feedstock preparation, catalytic pyrolysis at varying biomass-to-catalyst ratios, and characterization of the bio-oil using Gas Chromatography-Mass Spectrometry (GC–MS). Statistical analysis was subsequently performed to evaluate the significance of catalyst loading on product yield and molecular distribution. The optimization of the biomass-to-catalyst ratio was done using mean-based interpolation method (MIM).

A. Biomass Sample Collection

The biomass used in this study was *Achyranthes aspera* wood residue obtained from Ota, Ado–Odo Local Government Area, Ogun State, Nigeria. The feedstock was selected due to its local availability, renewable nature, and suitability for thermochemical conversion.

B. Sample Preparation

The biomass samples were milled using equipment in the Mechanical Central Workshop of Bells University of Technology, Ota, Nigeria, to ensure uniform particle size and effective heat transfer during pyrolysis. The milled wood residue was sieved to a particle size range of 0.0–0.5 mm (500 µm). The samples were weighed according to the calculated charge weight and a portion was pelletized for bomb calorimetric analysis to determine the heating value.

C. Experimental Setup

The experimental system consisted of a cylindrical carbon steel pyrolysis reactor heated by a 4-kW furnace. An ice-cooled condenser was used to collect condensable volatiles, while a temperature sensor monitored and controlled the reactor temperature before each experiment, the reactor was purged with nitrogen gas at a flow rate of 100 $mLmin^{-1}$ for 10 minutes to remove residual oxygen. During pyrolysis, a steady nitrogen flow rate of 15 $mLmin^{-1}$ was maintain to ensure an inert atmosphere. The biomass feedstock was preheated at 103 °C for 1 hour to eliminate bound moisture, after which the temperature was increased to 500 °C and maintained for 30 min residence time (or until gas evolution ceased). The resulting condensates were collected as bio-oil, and the solid residue was recovered as biochar. The general configuration of the pyrolysis unit is shown schematically in Figures 1 and pyrolysis experimental setup in Figure 2 (Oyebanji et al., 2023). Table 1 shows the list of the component parts of Pyrolysis experimental setup.

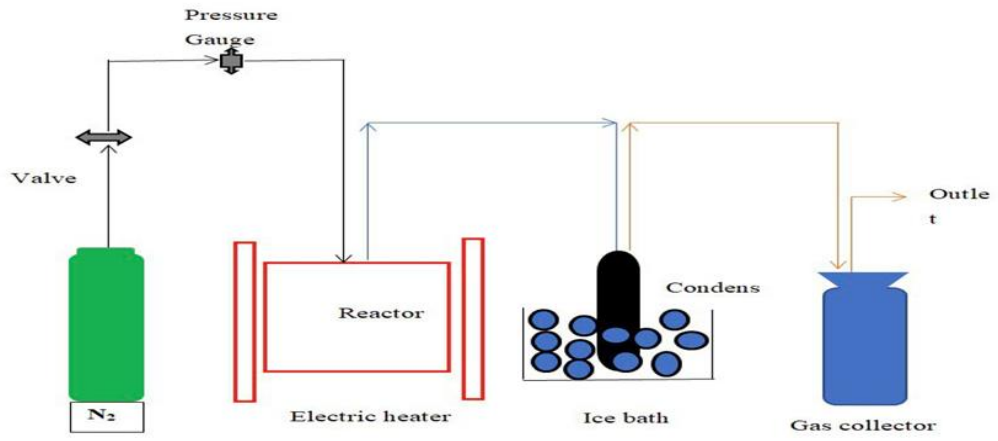

Figure 1. Schematic diagrams of pyrolysis apparatus.

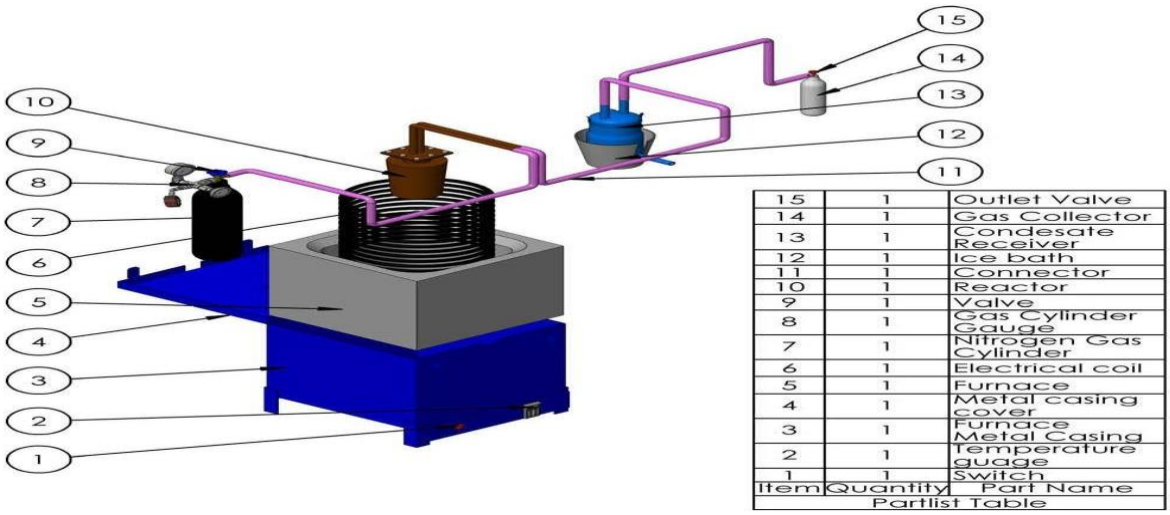

Figure 2. Pyrolysis experimental setup.

Table 1. List of the component parts of Pyrolysis experimental setup.

Label number of parts	Quantity of Part	Part Name
15	1	Outlet Valve
14	1	Gas Collector
13	1	Condensate 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

D. Experimental Procedure

Four biomass-to-zeolite Y catalyst ratios (100/0, 95/5, 90/10, and 85/15 wt.%) were tested under identical conditions of 500℃ and nitrogen flow rate maintained at 15 mL min^{-1} throughout pyrolysis to ensure reproducibility. After each run, the condensate (bio-oil) and solid residue (biochar) were weighed, while the gas yield was determined by mass balance. The product yields were calculated using the following expressions:

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

$$\%W_{Biochar} = \frac{W_{Biochar}}{W_{Biomass}} x\ 100\% \quad (2)$$

$$\%W_{Syngas} = 100\% - (\%W_{Bio-oil} + \%W_{Biochar}) \quad (3)$$

Where $W_{Biomass}, W_{Bio-oil}, \%W_{Biochar}$ and $\%W_{Syngas}$ represent the respective masses of the feedstock, liquid, solid, and gas products.

E. Gas Chromatography–Mass Spectrometry (GC–MS) Analysis

The molecular composition of the bio-oil samples obtained at different biomass-to-catalyst ratios was determined using Gas Chromatography-Mass Spectrometry (GC–MS) (Shimadzu QP2010 Plus). Separation was achieved on a capillary column (30 m × 0.25 mm, 0.25 μm film thickness). A 1 μL sample was injected in split mode (1:100), with helium as the carrier gas at a flow rate of 1.5 mL min^{-1}. Injector and transfer line temperatures were maintained at 220 °C and 290 °C, respectively, and the mass spectra were scanned over the 40–700 m/z range. The resulting chromatograms were interpreted to identify individual compounds, which were grouped into functional classes: phenols, catechols, furans, ketones, carboxylic acids, esters, aldehydes, and others; based on their structural and chemical characteristics.

F. Experimental Design and Statistical Analysis

A completely randomized design (CRD) was employed to evaluate the effects of catalyst loading on product yields and bio-oil composition. Analysis of Variance (ANOVA) was conducted at a significance level of $\alpha = 0.05$ to assess:

1. The influence of biomass-to-catalyst ratio (independent variable) on product yields (bio-oil, biochar, and syngas).
2. The effect of catalytic and non-catalytic pyrolysis on bio-oil composition.
3. The variation in compound classes identified by GC–MS across different catalyst loadings.

All statistical analyses were performed to determine whether differences among treatments were significant, and to establish relationships between catalyst ratio and chemical speciation of the resulting bio-oil.

G. Optimization of the Biomass-to-Catalyst Ratio

The optimization of the biomass-to-catalyst ratio was done using mean-based interpolation method. The optimization of the biomass-to-catalyst ratio is a critical component of this study, aimed at determining the most efficient and sustainable operating conditions for pyrolysis of the *Achyranthes aspera* Wood Residue. Unlike conventional optimization techniques that rely on complex computational algorithms or objective function minimization, this study adopts a mean-based interpolation method. This is a statistically grounded and physically interpretable approach that identifies the optimal operating value and range for pyrolysis of the *Achyranthes aspera* Wood Residue. The method is justified on the basis of equilibrium operating theory, practical biomass-to-catalyst ratio boundary constraints, and linear interpolation mathematics, as detailed in the subsequent sections. The mean-based interpolation method is computationally transparent, physically interpretable, and grounded in established statistical, mathematical, and engineering principles.

G.1. Optimization Methodology: The Mean-Based Interpolation Method

The Equilibrium Load Determination Using Mean-based Interpolation Method optimizes biomass-to-catalyst ratio through a structured four-step procedures. Each step is grounded in a specific statistical or mathematical operation, ensuring that the final optimal value is both computationally sound and physically interpretable. The steps are described in detail below:

(i) Step 1: Data Collection and biomass-to-catalysy ratio level Profiling

Data were collected on the effects of catalyst loading on product yields and bio-oil composition

(ii) Step 2: Computation of the Grand Mean Value

The grand mean was computed by averaging the each of the constituents of the pyrolysis of the *Achyranthes aspera* Wood Residue across all applicable four biomass-to-zeolite Y catalyst ratios (100/0, 95/5, 90/10, and 85/15 wt.%). The grand mean $\bar{P}$ for each product yield is expressed as:

$$\bar{P} = \frac{1}{n}\sum_{i=1}^{n} P_i \ (i = 1 \ to \ n) \quad (4)$$

Where:

P_i = parameter value at each biomass-to-zeolite Y catalyst ratio level

n = total number of valid biomass-to-zeolite Y catalyst ratio levels under study= 4

This mean value represents the equilibriusm operating value of the product yield; the moderate point between under-production and over-production.

(iii) Step 3: Identification of the Optimal Range

The grand mean $\bar{P}$ is then located within the practical optimization domain to determine which biomass-to-zeolite Y catalyst ratio interval it falls into. The possible optimal ranges are defined as follows:

If $\bar{P}$ lies within $P_{100/0} \leq P \leq P_{95/5} \implies$ Optimal Range: 0–5% catalytic loading

If $\bar{P}$ lies within $P_{95/5} \leq P \leq P_{90/10} \implies$ Optimal Range: 5–10% catalytic loading

If $\bar{P}$ lies within $P_{90/10} \leq P \leq P_{85/15} \implies$ Optimal Range: 10–15% catalytic loading

The interval within which $\bar{P}$ naturally falls defines the optimal operating range of the catalytic loading for the pyrolysis of the the *Achyranthes aspera* Wood Residue.

(iv) Step 4: Determination of the Optimal Value by Linear Interpolation

Once the optimal range is identified, linear interpolation is applied to determine the precise catalytic loading x that corresponds to the grand mean value $\bar{P}$ within the identified range. The linear interpolation formula is given as:

$$x = L_1 + \frac{(P - P_1)}{(P_2 - P_1)} \times (L_2 - L_1) \quad (5)$$

Where:

x = optimal load operating point

L_1 = lower load boundary of the identified range

L_2 = upper load boundary of the identified range

P_1 = parameter value at load L_1

P_2 = parameter value at load L_2

$\bar{P}$ = grand mean of the parameter

III. RESULTS AND DISCUSSIONS

This section presents the experimental findings obtained from the catalytic pyrolysis of Achyranthes aspera wood residue using zeolite Y catalyst at varying biomass-to-catalyst ratios (100/0, 95/5, 90/10, and 85/15). The results include the yield distributions of bio-oil, biochar, and syngas, as well as the molecular composition of the bio-oil determined through Gas Chromatography–Mass Spectrometry (GC–MS) analysis.

Analysis of Variance (ANOVA) was performed to statistically evaluate:

(i) the significance of the catalyst loading on the product yields, and

(ii) the effect of catalytic and non-catalytic conditions on the chemical composition of the bio-oil.

The results are presented in the following subsections, which describe the variations in product distribution, molecular characteristics, and compositional shifts resulting from catalytic influence.

A. Product Yield Distribution from Catalytic Pyrolysis of Achyranthes aspera Wood Residue

Zeolite Y loading significantly altered product distribution, with bio-oil yield decreasing from 51.85 to 29.45 wt.% as catalyst proportion increased from 0 to 15 wt.% (Table 2). The catalytic pyrolysis of Achyranthes aspera wood residue was carried out at 500 °C using zeolite Y catalyst at biomass-to-catalyst

ratios of 100/0, 95/5, 90/10, and 85/15 (wt.%). The resulting product yields of bio-oil, biochar, and syngas are summarized in Table 2 and illustrated in Figure 3.

Under the non-catalytic condition (100/0), the process produced 51.85 wt.% bio-oil, 25.75 wt.% biochar, and 22.40 wt.% syngas. A slight increase in bio-oil yield was observed at low catalyst loading (95/5), reaching 52.95 wt.%, while biochar and syngas yields were 22.00 wt.% and 25.05 wt.%, respectively. As the catalyst proportion increased to 90/10 and 85/15, the bio-oil yield declined progressively to 46.75 wt.% and 29.45 wt.%, whereas the syngas yield rose sharply to 31.95 wt.% and 53.50 wt.%, respectively. Biochar yield exhibited a gradual decrease from 25.75 wt.% to 17.05 wt.% across the tested ratios as shown in Figure 3. These results show that varying the zeolite Y loading influenced the distribution of the three product phases. Higher catalyst ratios corresponded to lower liquid yields and higher gaseous fractions, while biochar yield changed only slightly. A detailed interpretation of the catalytic mechanism underlying these observations is provided in Section 4.1.

To statistically verify the observed differences, Analysis of Variance (ANOVA) was conducted on the product yields from catalytic and non-catalytic runs (Table 3). The results revealed a significant difference ($p < 0.05$) among the three product types bio-oil, biochar, and syngas indicating that the presence of the catalyst affected the overall product distribution, consistent with the findings of Efeovbokhan et al. (2020). More so, differences among the catalyst loadings themselves were statistically significant, suggesting that small additions of zeolite Y (5 wt.%) were sufficient to influence product formation, with higher loadings yielding statistically distinct changes.

Table 2. Product yield distribution from catalytic pyrolysis of *Achyranthes aspera* wood residue at 500 °C using zeolite Y catalyst at varying biomass-to-catalyst ratios.

Biomass-to-Catalyst Ratio	Bio-oil (wt.%)	Biochar (wt.%)	Syngas (wt.%)
100/0 (non-catalytic)	51.85	25.75	22.40
95/5	52.95	22.00	25.05
90/10	46.75	21.30	31.95
85/15	29.45	17.05	53.50

B. Molecular Composition of Bio-oil from Catalytic Pyrolysis of Achyranthes aspera Wood Residue

Zeolite Y catalysis markedly transformed the molecular profile of bio-oil, with phenolic compounds increasing from 19.95% to 33.08% while carboxylic acids decreased from 5.28% to 4.19% as catalyst loading increased (Table 4). The chemical composition of bio-oils produced at different biomass-to-zeolite Y catalyst ratios (100/0, 95/5, 90/10, and 85/15 wt.%) was determined using Gas Chromatography–Mass Spectrometry (GC–MS). Representative chromatograms for the analyzed samples are shown in Figure 4, while the identified compound classes and their relative proportions are summarized in Table 4. Across all conditions, the major compound groups detected were phenols, catechols, carboxylic acids, aldehydes, ketones, esters, and furans, consistent with the decomposition of lignin, cellulose, and hemicellulose components of the biomass as shown in Figure 4. Under the non-catalytic condition (100/0), the bio-oil was dominated by oxygenated compounds, with phenolics accounting for 19.95 %, carboxylic acids for 5.28 %, and ketones for 13.13 % of the total peak area.

Introducing zeolite Y catalyst altered the molecular distribution significantly. At 95/5 wt.% catalyst loading, the proportion of phenolic compounds increased to 30.92 %, accompanied by a moderate reduction in carboxylic acids and aldehydes, similar to the findings of Samolada et al. (2000), Pattiya et al. (2008), and Pehlivan (2023). Further increases in catalyst ratio (90/10 and 85/15) enhanced the conversion of oxygen-rich species into lighter and more aromatic structures, with total phenols reaching 33.08 % at 85/15. Simultaneously, carboxylic acids declined sharply to 4.19 %, indicating effective catalytic deoxygenation and secondary cracking reactions promoted by the acidic sites of zeolite Y. The results indicate that for all biomass-to-catalyst ratios containing catalyst (95/5, 90/10, and 85/15), phenol had the highest percentage composition in the bio-oil, consistent with the findings of Efeovbokhan et al. (2020) and Oyebanji et al. (2023b).

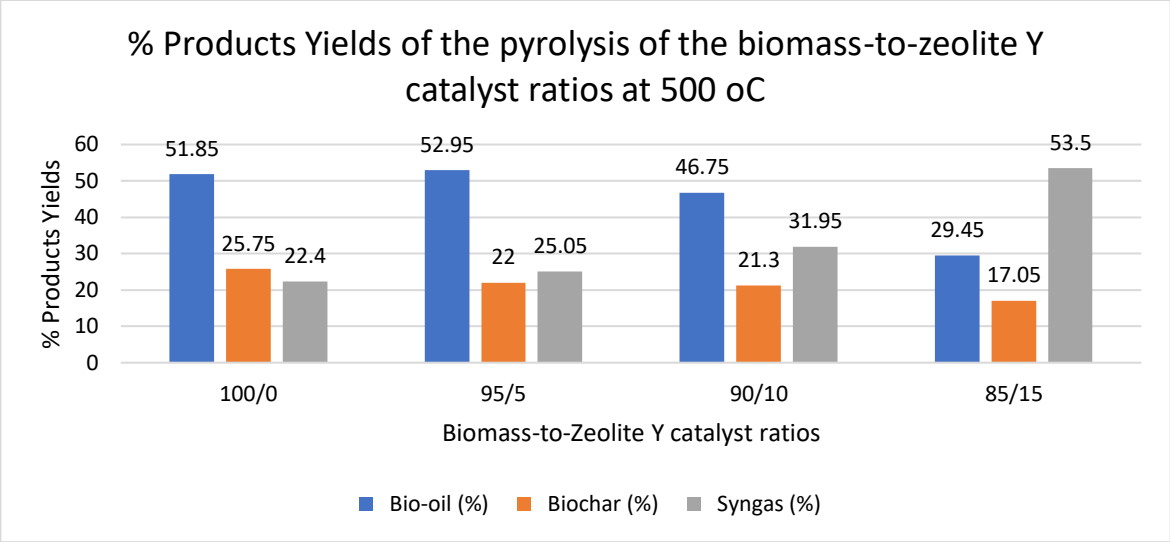

Figure 3. Variation in product yields (bio-oil, biochar, and syngas) obtained from catalytic and non-catalytic pyrolysis of Achyranthes aspera wood residue at 500 °C using different biomass-to-zeolite Y catalyst ratios.

Table 3. ANOVA for product yield distribution from catalytic pyrolysis of Achyranthes aspera wood residue at 500 °C.

Sources	Degree of Freedom	Sum of Square	Mean of Square	F-value	F-critical	Significant
Product Yields	2	1125.82	562.91	5.12	3.01	Significant ($p < 0.05$)
Error	9	989.61	109.96	-	-	-
Total	11	2115.43	-	-	-	-

The observed trend suggests that catalytic upgrading favored de-methoxylation, decarboxylation, and dehydration pathways, thereby reducing oxygen-functional groups while enriching phenolic content. The total number of detectable peaks also decreased with increasing catalyst loading, reflecting improved selectivity toward more stable molecular classes.

To verify these compositional changes statistically, Analysis of Variance (ANOVA) was performed on the relative abundance of compound classes across the four catalyst ratios (Table 5). The ANOVA results showed a highly significant difference ($p < 0.05$) among the compound classes, confirming that catalyst loading had a measurable influence on bio-oil composition. Post-hoc comparison indicated that the differences between non-catalytic (100/0) and high-catalyst (85/15) conditions were the most pronounced, especially for phenols and carboxylic acids. The variations between 95/5 and 90/10 ratios were statistically minor, suggesting that catalytic activity approached saturation beyond moderate loadings. More so, the Table 4 revealed that the compound classes are not equally distributed in the bio-oil: Phenols (mean =29.01%) and Catechols (mean = 21.94%) dominate, while Cresols (mean = 2.91%) and Furans (Mean = 5.29%) are minor constituents. Zeolite Y catalysis consistently enhanced the phenolic fraction while suppressing oxygenated acids and esters across all catalyst loadings.

Overall, GC–MS analysis and ANOVA results reveal that zeolite Y catalysis markedly transformed the molecular profile of the bio-oil, enriching aromatic phenolic species while suppressing oxygenated acids and carbonyls. These changes are indicative of effective catalytic upgrading and are further discussed in Section 4.2.

Table 4. Relative distribution of compound classes in bio-oils obtained from catalytic and non-catalytic pyrolysis of Achyranthes aspera wood residue at 500 °C.

Biomass-to-catalyst ratio	Phenols (%)	Cresol (%)	Furans (%)	Ketone (%)	Carboxylic Acid (%)	Esters and Aldehydes (%)	Catechol (%)	Others (%)
100/0	19.95	2.71	2.39	13.13	5.28	18.12	21.26	17.16
95/5	30.92	2.00	2.10	10.63	13.28	12.42	20.82	7.83
90/10	32.08	2.54	7.37	11.50	6.16	2.87	22.68	14.80
85/15	33.08	1.50	9.31	12.20	4.19	1.87	22.99	14.86
Grand Mean	29.01	2.19	5.29	11.87	7.23	8.82	21.94	13.66

Table 5. ANOVA summary for compound-class Composition of bio-oils from catalytic pyrolysis of the biomass of the *achyranthes aspera* wood residue.

Sources	Degree of Freedom	Sum of Square	Mean of Square	F-value	F-critical	Significant
Compound Classes	7	2251.8	321.69	17.49	2.42	Significant ($p < 0.05$)
Error	24	441.36	18.39	-	-	-
Total	31	2693.19	-	-	-	-

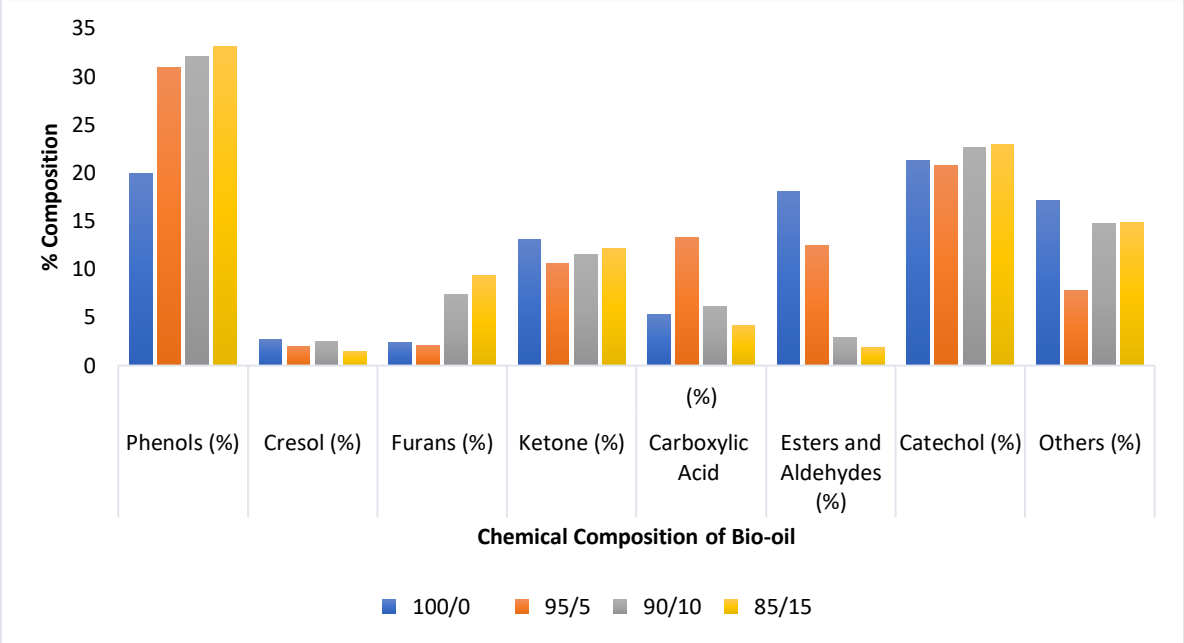

Figure 4. GC–MS chromatograms of bio-oils obtained from catalytic and non-catalytic pyrolysis of Achyranthes aspera wood residue at 500 °C, showing variations in peak intensity and compound distribution with increasing zeolite Y catalyst loading.

C. Optimization of Catalyst Loading Based on Process Objectives

The experimental results revealed that the optimal biomass-to-catalyst ratio depends on the intended application and process objectives. Analysis of product yield and composition data across all catalyst loadings indicates three distinct optimization scenarios:

1. For maximum bio-oil yield: The 95/5 ratio is optimal, producing 52.95 wt.% bio-oil while maintaining moderate catalytic upgrading, with a phenolic content of 30.92%.

2. For maximum phenolic enrichment: The 85/15 ratio is optimal, achieving the highest phenolic concentration (33.08%) and maximum acid reduction (4.19%), though at the expense of bio-oil yield (29.45 wt.%).

3. For balanced performance: The 90/10 ratio provides a practical compromise, delivering a reasonable bio-oil yield (46.75 wt.%) and substantial phenolic enrichment (32.08%) with effective deoxygenation.

The selection of an optimal catalyst loading should therefore be guided by downstream application requirements: fuel production may prioritize yield (95/5), specialty chemical recovery may prioritize phenolic content (85/15), while integrated biorefineries may benefit from the balanced approach (90/10).

D. Mean-Based Interpolation Optimization of Biomass-to-Catalyst Ratio

To determine a statistically grounded and process-relevant optimal biomass-to-catalyst ratio, a mean-based linear interpolation method was applied to the experimentally obtained product yield data. This approach is justified on the basis that bio-oil yield represents the primary target output of this catalytic pyrolysis process: bio-oil is the energy-dense liquid fraction of highest economic and practical value for downstream fuel and chemical applications, while biochar and syngas are co-products whose yields must be managed concurrently. By anchoring the optimization to the arithmetic mean of each product's yield distribution across the four tested catalyst loading levels, the method identifies the catalyst loading at which the bio-oil yield equals its statistical central tendency while biochar and syngas yields remain within their own mean-defined bounds. This mean-based criterion is scientifically valid because it uses the experimental dataset itself as the reference frame, avoids extrapolation beyond the tested loading range, and produces a single quantified optimum value that is reproducible and verifiable from the raw data.

The arithmetic means of the four experimentally measured product yields (at 0, 5, 10, and 15 wt.% catalyst loading) were first computed as follows. The mean bio-oil yield was determined as:

$$\text{Mean bio-oil yield} = \frac{51.85 + 52.95 + 46.75 + 29.45}{4} = 45.25\ wt.\% \quad (6)$$

The mean biochar yield was determined as:

$$\text{Mean biochar yield} = \frac{25.75 + 22.00 + 21.30 + 17.05}{4} = 21.5250\ wt.\%. \quad (7)$$

Mean syngas yield was determined as:

$$\text{Mean syngas yield} = \frac{22.40 + 25.05 + 31.95 + 53.50}{4} = 33.225\ wt.\% \quad (8)$$

Inspection of the experimental data confirms that all three product means fall exclusively within the interval bounded by the 90/10 and 85/15 biomass-to-catalyst ratios (i.e., between 10 wt.% and 15 wt.% catalyst loading): the bio-oil mean of 45.25 wt.% lies between the observed values of 46.75 wt.% (90/10) and 29.45 wt.% (85/15); the biochar mean of 21.525 wt.% lies between 21.30 wt.% (90/10) and 17.05 wt.% (85/15); and the syngas mean of 33.225 wt.% lies between 31.95 wt.% (90/10) and 53.50 wt.% (85/15). This simultaneous convergence of all three product means within the same loading interval establishes the optimal catalytic loading range as 10–15 wt.% zeolite Y, corresponding to biomass-to-catalyst ratios of 90/10 to 85/15.

To determine the precise optimal catalyst loading value within this range, linear interpolation was applied using the bio-oil yield as the primary optimization variable. Bio-oil yield is selected as the governing variable because it is the principal product of economic and energetic interest in this study, and its mean represents the balanced central output across the tested process window. The interpolation

employs the two flanking experimental data points that bracket the bio-oil mean: at 10 wt.% catalyst loading, bio-oil yield = 46.75 wt.%; at 15 wt.% catalyst loading, bio-oil yield = 29.45 wt.%; and the target yield value is the mean bio-oil yield of 45.25 wt.%.

Applying the linear interpolation formula:

$$\frac{x-15}{10-15}=\frac{45.25-29.45}{46.75-29.45}$$
$$x=10.43\ wt.\%$$

The interpolated optimal catalyst loading value is therefore 10.43 wt.% zeolite Y, corresponding to an optimal biomass-to-catalyst ratio of approximately 89.57/10.43 (expressed as ≈ 89.6/10.4). At this precise loading, linear interpolation yields a bio-oil yield of 45.25 wt.% (equal to the mean bio-oil yield), a biochar yield of 20.93 wt.%, and a syngas yield of 33.82 wt.%, with the three values summing to 100.00 wt.%, confirming the internal consistency of the interpolation. These co-product yields at the optimal point are both below their respective experimental means (mean biochar = 21.525 wt.%; mean syngas = 33.225 wt.%), which further confirms that the identified optimum satisfies a balanced, mean-referenced criterion across all three product fractions simultaneously.

The results of the mean-based interpolation optimization are summarized in Table 6. The optimal catalytic loading range of 10–15 wt.% zeolite Y (biomass-to-catalyst ratio 90/10 to 85/15) defines the operational window within which the pyrolysis process transitions through the mean yields of all three products. Within this window, the single optimal catalyst loading value of 10.43 wt.% (biomass-to-catalyst ratio ≈ 89.57/10.43) represents the interpolated point at which bio-oil yield attains its arithmetic mean value of 45.25 wt.%, providing a balanced output across all three product phases. This value lies close to but slightly above the experimentally tested 90/10 condition (46.75 wt.% bio-oil), confirming that practical process operation at the 90/10 ratio represents a close approximation to the analytically derived optimum.

Table 6. Mean-Based Interpolation Optimization: Arithmetic Means, Optimal Loading Range, and Optimal Loading Value for Bio-oil, Biochar, and Syngas from Catalytic Pyrolysis of Achyranthes aspera Wood Residue at 500 °C.

Parameter	Bio-oil	Biochar	Syngas	Optimal Loading
Arithmetic Mean (wt.%)	45.25	21.5250	33.2250	-
Mean bracketed by ratio	90/10 – 85/15	90/10 – 85/15	90/10 – 85/15	Range: 90/10 – 85/15
Optimal catalyst range (wt.%)	10 – 15 wt.% (Biomass/Catalyst: 90/10 – 85/15)			10 – 15 wt.%
Optimal value (wt.%)	45.25	20.9315	33.8185	10.43 wt.% (≈89.57/10.43)

It is noteworthy that the optimal catalyst loading value of 10.43 wt.% lies only 0.43 percentage points beyond the experimentally tested 90/10 condition. This proximity confirms that the 90/10 ratio is the nearest practically feasible operating point to the theoretical optimum, and validates its selection as the recommended working ratio for processes where bio-oil yield and catalytic upgrading quality must be simultaneously balanced. The mean-based interpolation method therefore provides a rigorous, data-driven quantitative justification for a recommendation that was previously offered only qualitatively in Section 3.3, and demonstrates that incremental catalyst addition beyond 10 wt.% yields diminishing bio-oil returns while progressively increasing syngas output. This analysis is further discussed in relation to process trade-offs and practical implementation in Section 4.4 and Section 4.9 of this paper.

IV. **Discussion**

A. Discussion of Product Yield Variation

The inverse relationship between zeolite Y loading and bio-oil yield, coupled with proportional syngas enhancement, demonstrates the catalyst's strong promotion of secondary cracking and deoxygenation reactions within the vapor phase. The observed variation in product yields with changing zeolite Y loading reflects the strong influence of catalytic activity on the thermal decomposition behavior of *Achyranthes aspera* wood residue. In the non-catalytic run, the relatively high bio-oil yield (51.85 wt.%) and moderate gas fraction (22.40 wt.%) indicate that most of the primary pyrolysis vapors condensed without extensive secondary reactions, consistent with the result of Jamilatun et al. (2025). This outcome is typical for lignocellulosic feedstocks decomposed under purely thermal conditions, where depolymerization of hemicellulose and cellulose primarily generates condensable volatiles.

Introducing zeolite Y at low loading (95/5) marginally increased the liquid yield, suggesting that limited catalytic contact enhanced vapor cracking and condensation stability without extensive gas evolution, similar to the findings of Efeovbokhan et al. (2020). At higher catalyst loadings (90/10 and 85/15), however, the bio-oil yield declined markedly while syngas production increased, a trend also reported by Kabakci and Hacibektasoglu (2017), Zhang et al. (2020), Wang et al. (2022), Zhu et al. (2022), and Reza et al. (2023a, 2023b). This shift arises from the acidic sites and pore structure of zeolite Y, which promote secondary cracking, deoxygenation, and aromatization reactions of primary vapors within the reactor. These reactions convert heavy oxygenated molecules into smaller hydrocarbons, CO, CO_2, and light gases, thereby reducing the condensable fraction. Similar yield trends have been reported for zeolite-catalyzed pyrolysis of sawdust, rice husk, and microalgae, where increasing catalyst proportion enhances vapor-phase cracking and gas formation (Mante et al., 2013; Wang et al., 2015; Iisa et al., 2023; Awodun et al., 2025).

The gradual reduction in biochar yield with rising catalyst loading (from 25.75 to 17.05 wt.%) further supports the occurrence of more complete thermal degradation, as reported by the reported by Rollage et al. (2022) and Jamilatun et al. (2025). Zeolite presence facilitates heat transfer and promotes volatilization of solid carbonaceous intermediates, leaving less fixed carbon in the residue. Nevertheless, the relatively moderate change in char yield compared with liquid and gas fractions indicates that the catalyst predominantly influenced vapor-phase reactions rather than the primary decomposition of the solid biomass matrix.

These findings highlight the importance of multi-objective optimization in catalytic pyrolysis. Rather than identifying a single “optimal” condition, the results reveal three distinct optima based on process priorities:

(1) Maximizing bio-oil yield at the 95/5 ratio (52.95 wt.%), suitable for fuel production where volumetric output is critical;

(2) Maximizing phenolic content at the 85/15 ratio (33.08%), ideal for the extraction of high-value chemicals such as phenolic derivatives for resin or pharmaceutical applications; and

(3) Achieving balanced performance at the 90/10 ratio, which provides a moderate bio-oil yield (46.75 wt.%) with substantial catalytic upgrading (32.08% phenolics), appropriate for integrated biorefinery concepts.

This multi-criteria perspective is essential for industrial implementation, where economic viability depends on aligning catalyst loading with specific product valorization strategies (Kumar and Strezov, 2021; Awodun et al., 2025).

The ANOVA results confirmed that the overall differences among product types were statistically significant at $p < 0.05$, validating the catalytic impact on yield distribution.

From a process-optimization standpoint, these findings imply that low catalyst loading can provide sufficient vapor upgrading while maintaining a reasonable liquid yield, whereas higher catalyst ratios favor gas production suitable for heat or syngas-based applications. Thus, the balance between energy-

dense bio-oil generation and gaseous fuel enhancement depends on the intended end-use of the pyrolysis products.

B. Discussion of Catalytic Influence on Bio-oil Composition

The 65.8% enhancement in phenolic content and concurrent 20.64% reduction in carboxylic acids confirm that zeolite Y's acidic sites effectively catalyzed deoxygenation pathways while promoting aromatic enrichment through demethoxylation and decarboxylation mechanisms. The GC-MS results demonstrated that the molecular composition of the bio-oil from Achyranthes aspera wood residue changed markedly with the introduction of zeolite Y catalyst. Under non-catalytic conditions, the bio-oil contained a wide spectrum of oxygenated compounds phenols, carboxylic acids, aldehydes, ketones, esters, and furans typical of lignocellulosic pyrolysis liquids, as reported by Valle et al., (2022); Boas et al. (2025). These species arise from the cleavage of ether and C–O–C linkages in lignin and from the depolymerization and dehydration of cellulose and hemicellulose. Their presence explains the high oxygen content, acidity, and chemical instability of non-catalytic bio-oils reported in similar studies (Pehlivan, 2023; Diaz et al., 2024).

With zeolite Y addition, the relative concentration of phenolic compounds increased progressively from 19.95% in the non-catalytic run to 33.08% at the 85/15 biomass-to-catalyst ratio, while oxygen-rich carboxylic acids declined from 5.28% to 4.19%, consistent with the findings of Iliopoulou et al. (2007), Zhou et al. (2013), and Ratnasari (2021). This transformation reflects the catalyst's strong acidic and shape-selective properties (Liu et al., 2020), which promote deoxygenation and aromatic upgrading through several pathways:

1. Decarboxylation and decarbonylation, converting acids and aldehydes to CO_2 and CO (Sayed, 2025);

2. Dehydration, eliminating water from alcohols and ketones to form unsaturated intermediates.

Such reactions reduce oxygen functionality and enhance hydrocarbon-type products, yielding more thermally and chemically stable liquids. Comparable behavior has been reported for zeolite Y, ZSM-5, and H-Beta catalysts during the pyrolysis of woody and herbaceous feedstocks (Panwar and Paul, 2020; Sun et al., 2025).

The decrease in the total number of detectable GC–MS peaks with higher catalyst loading further suggests increased product selectivity. As secondary cracking and condensation occur within the zeolite pores, unstable oxygenates and heavy tars are converted into smaller, more uniform aromatic species. This catalytic selectivity accounts for the pronounced enrichment of phenols and catechols in the 85/15 sample, consistent with the improved deoxygenation efficiency indicated by reduced carboxylic-acid peaks, as observed by Pehlivan et al. (2023).

The ANOVA analysis for bio-oil composition confirmed that the differences among compound classes were statistically significant ($p < 0.05$), verifying that the observed compositional shifts were not random but directly linked to catalyst loading. Post-hoc comparisons indicated that the most substantial changes occurred between the non-catalytic and the highest catalyst condition, emphasizing the catalyst's effectiveness in modifying vapor chemistry even at moderate temperatures. However, the relatively small difference between 90/10 and 85/15 ratios suggests that the catalytic sites of zeolite Y approached saturation at higher loadings, producing diminishing returns beyond a critical threshold.

From a practical standpoint, these compositional changes are advantageous. An increase in phenolic compounds enhances the heating value, stability, and potential for fine-chemical recovery from bio-oil, while the reduction in acids mitigates corrosivity and improves compatibility with downstream upgrading units. Therefore, moderate zeolite Y inclusion (5–10 wt.%) provides a balance between effective deoxygenation and acceptable liquid yield, whereas excessive catalyst addition primarily drives gas formation rather than further molecular improvement.

Several prior studies have examined zeolite-catalyzed pyrolysis of lignocellulosic biomass, including sawdust (Mante et al., 2013), rice husk (Wang et al., 2015), and cassava rhizome (Pattiya et al., 2008); however, these investigations differ from the present work in feedstock composition, catalyst loading range, and analytical scope. The novelty of this study is therefore threefold. First, it presents the first systematic characterization of bio-oil derived from Achyranthes aspera wood residue, an underutilized Nigerian agro-residue not previously explored as a pyrolysis feedstock, thereby expanding the documented portfolio of viable lignocellulosic materials. Second, it provides a quantitative mapping of zeolite Y loading effects across four discrete biomass-to-catalyst ratios (100/0, 95/5, 90/10, and 85/15 wt.%), generating the dose–response data needed to guide practical catalyst selection that is absent from earlier qualitative reports. Third, by combining product yield analysis with compound-class-level GC–MS profiling and ANOVA-based statistical validation, it advances beyond single-point characterization to establish statistically significant composition–loading relationships, particularly the 65.8% phenolic enrichment and 20.64% carboxylic acid reduction, which have not previously been reported for this feedstock–catalyst pairing. Together, these contributions address a documented knowledge gap and provide a reproducible dataset that can inform catalyst selection strategies for zeolite-catalyzed pyrolysis of tropical agricultural residues.

C. Proposed Reaction Mechanisms and Zeolite Y Catalytic Pathways

The selective enrichment of phenolic compounds over other oxygenates suggests that zeolite Y's three-dimensional pore structure (7.4 Å supercages) and moderate Brønsted acidity preferentially accommodate and convert lignin-derived oligomers through shape-selective cracking pathways. The catalytic transformation observed in this study can be attributed to several synergistic reaction mechanisms occurring within zeolite Y's acidic framework. The primary pathways include:

1. Demethoxylation: Methoxy groups (-OCH_3) attached to aromatic rings undergo catalytic cleavage, converting guaiacols and syringols to simpler phenols while releasing methanol and formaldehyde, which further decompose to CO and light gases (Oyebanji et al., 2020).

2. Decarboxylation and Decarbonylation: Carboxylic acids and aldehydes undergo C-C bond cleavage at Brønsted acid sites, releasing CO_2 and CO respectively, thereby reducing oxygen functionality (Sayed, 2025).

3. Dehydration: Hydroxyl groups on aliphatic chains undergo elimination reactions, forming unsaturated intermediates that either cyclize to aromatics or crack to smaller gaseous products.

4. Aromatization: The zeolite's confined pore environment promotes Diels-Alder-type cyclization reactions and hydrogen transfer, converting aliphatic oxygenates to aromatic phenolic structures.

The moderate acidity of zeolite Y (weaker than ZSM-5) appears optimal for deoxygenation without excessive C-C bond cracking that would otherwise produce predominantly gaseous products. This explains why phenolic selectivity peaked at 85/15 ratio, where sufficient acid sites were available for complete vapor-phase upgrading (Oyebanji et al., 2023).

D. Multi-Objective Optimization and Process Trade-offs

The contrasting optima identified 95/5 for maximum yield, 85/15 for maximum quality, and 90/10 for balanced performance illustrate the fundamental trade-off between liquid fuel production and chemical upgrading that must guide industrial catalyst selection.

From a process optimization perspective, the choice of catalyst loading depends critically on the intended application and economic priorities:

Scenario 1: Fuel-Oriented Biorefinery – When the primary objective is producing liquid transportation fuel or fuel blending components, the 95/5 catalyst ratio offers optimal economics. The 52.95 wt.% bio-oil yield maximizes volumetric output while achieving moderate upgrading (30.92% phenolics), sufficient for subsequent hydrotreating or co-processing with petroleum fractions.

Scenario 2: Chemical-Oriented Biorefinery – For facilities targeting high-value phenolic extraction (phenol, cresols, catechols for resin or pharmaceutical industries), the 85/15 ratio justifies the lower liquid yield through superior product quality. At 33.08% phenolic content and only 4.19% acids, the bio-oil requires less downstream purification, potentially offsetting the yield penalty through higher product value.

Scenario 3: Integrated Biorefinery – Industrial facilities seeking to balance liquid fuel production with chemical co-product recovery may find the 90/10 ratio optimal. The 46.75 wt.% bio-oil yield remains economically viable while 32.08% phenolic content enables profitable chemical extraction, and the 31.95 wt.% syngas can be utilized for process heat or Fischer-Tropsch synthesis.

This multi-objective framework demonstrates that catalyst optimization in biomass pyrolysis cannot be reduced to a single "best" condition but must align with specific biorefinery business models and market conditions.

A critical practical implication of these findings concerns the economic feasibility of increasing catalyst loading. Moving from the 95/5 to the 85/15 ratio reduces bio-oil yield by 23.5 percentage points (from 52.95 to 29.45 wt.%), representing a near-halving of the liquid product. In an industrial context, this liquid yield penalty carries significant cost consequences: larger feed throughput is required to maintain a given bio-oil output, catalyst procurement and regeneration costs increase proportionally, and downstream storage and transport infrastructure may be underutilized. These costs must be weighed against the quality gains specifically the 65.8% relative increase in phenolic content which are only economically justifiable if the phenolic fraction commands sufficiently higher market value than the displaced bio-oil volume. For fuel-blending applications where volumetric yield governs revenue, the 85/15 loading is likely sub-optimal regardless of compositional quality. Conversely, for high-value specialty chemical recovery (e.g., pharmaceutical-grade phenol or catechol), the composition premium may justify the yield cost. It is also important to note that the large increase in syngas yield at higher catalyst loadings (from 22.40 wt.% at 100/0 to 53.50 wt.% at 85/15) represents a potential co-product opportunity the elevated syngas fraction could be valorized for process heat recovery or Fischer–Tropsch liquid synthesis which partially offsets the liquid-yield loss when assessing overall process economics. Future techno-economic analysis should quantify these trade-offs explicitly to determine the catalyst-loading optima under realistic market pricing scenarios for bio-oil, phenolics, and syngas.

E. Positioning of Contribution Relative to Existing Studies (Novelty Clarification)

Catalytic pyrolysis of lignocellulosic biomass using zeolite-based catalysts has been widely reported; however, the present study contributes new insights in two important respects. First, Achyranthes aspera wood residue represents a previously unexplored feedstock in catalytic pyrolysis, particularly with zeolite Y. While prior studies have focused on conventional biomass such as sawdust, rice husk, and agricultural residues, the thermochemical behavior and catalytic upgrading response of A. aspera have not been systematically quantified. This work therefore expands the feedstock base for catalytic pyrolysis and provides foundational data for its valorization.

Second, beyond feedstock novelty, this study provides a quantitative evaluation of catalyst loading thresholds, explicitly linking biomass-to-catalyst ratio with product distribution and molecular composition. Unlike many prior works that report general trends, this study identifies a distinct transition window (5–10 wt.% catalyst) beyond which further catalyst addition yields diminishing compositional benefits but significant liquid yield penalties. This quantitative trade-off analysis represents a key contribution toward process optimization and scale-up considerations. Thus, the novelty of this work lies in the combined contribution of feedstock evaluation and quantitative elucidation of catalyst-loading-dependent trade-offs, rather than catalyst selection alone.

F. Influence of Zeolite Y on Product Distribution: Carbon Redistribution Mechanism

The observed decrease in bio-oil yield (51.85 → 29.45 wt.%) and corresponding increase in syngas production (22.40 → 53.50 wt.%) with increasing catalyst loading demonstrates a catalyst-induced shift in carbon distribution pathways. Rather than representing a simple loss of liquid product, this trend reflects enhanced secondary vapor-phase reactions promoted by the acidic sites of zeolite Y. At low catalyst loading (95/5), a slight increase in bio-oil yield suggests that limited catalytic interaction improves vapor stabilization and condensation efficiency. However, at higher catalyst loadings (90/10 and 85/15), extensive secondary cracking, deoxygenation, and fragmentation reactions dominate. These include:

(i) decarboxylation and decarbonylation, producing CO_2 and CO;
(ii) dehydration reactions, forming water and unsaturated intermediates; and
(iii) cracking of large oxygenates into permanent gases and light hydrocarbons.

As a result, condensable vapors are increasingly converted into non-condensable gases, leading to reduced liquid yield and increased gas formation. This behavior indicates a transition from a liquid-production regime to a gas-generation regime, controlled by catalyst loading. The relatively smaller reduction in biochar yield further suggests that zeolite Y primarily influences vapor-phase upgrading rather than primary biomass decomposition.

G. Catalytic Upgrading and Molecular Transformation of Bio-oil

GC–MS analysis revealed significant compositional changes in the bio-oil with increasing catalyst loading, notably a rise in phenolic compounds (19.95 → 33.08%) and a reduction in carboxylic acids (5.28 → 4.19%). These changes indicate effective catalytic deoxygenation and aromatic enrichment, driven by zeolite Y's Brønsted acidity and pore structure. The increase in phenolics is attributed to:

(i) demethoxylation of lignin-derived compounds;
(ii) selective cracking and rearrangement of oxygenated intermediates; and
(iii) aromatization within the zeolite pore structure. Simultaneously, the reduction in acidic compounds reflects the removal of oxygen functional groups via decarboxylation and dehydration pathways, contributing to improved chemical stability and reduced corrosivity. However, it is important to note that GC–MS provides only semi-quantitative information based on relative peak areas and primarily detects volatile and thermally stable compounds. Heavier fractions, oligomeric species, and water content are not fully captured. Therefore, while the observed increase in phenolic content and reduction in acids suggest improved bio-oil quality, these conclusions should be interpreted as indicative rather than definitive, pending further physicochemical characterization such as heating value, viscosity, and elemental composition.

H. Trade-offs Between Catalyst Loading, Bio-oil Yield, and Product Quality

A key outcome of this study is the identification of a fundamental trade-off between bio-oil yield and degree of catalytic upgrading. Increasing catalyst loading enhances deoxygenation and aromatic enrichment but simultaneously reduces liquid yield due to excessive secondary cracking. This trade-off leads to three distinct operational regimes: (i) low catalyst loading (5 wt.%), which maximizes bio-oil yield with moderate upgrading; (ii) intermediate loading (10 wt.%), which balances yield and compositional improvement; and (iii) high loading (15 wt.%), which maximizes upgrading but significantly reduces liquid yield. The relatively small differences between the 90/10 and 85/15 ratios in compositional improvement, compared with the substantial drop in bio-oil yield (46.75 → 29.45 wt.%), indicate diminishing returns at higher catalyst loadings. This suggests that the active catalytic sites approach saturation, beyond which additional catalyst primarily promotes over-cracking rather than further upgrading.

I. Practical Feasibility and Process Implications

From an industrial perspective, the selection of catalyst loading must consider both technical performance and economic feasibility. While higher catalyst loading improves deoxygenation, the associated loss in liquid yield may reduce overall process efficiency for fuel-oriented applications. For fuel production, where volumetric liquid yield is critical, lower catalyst loading (≈5 wt.%) is more practical, providing high bio-oil output with acceptable upgrading. For chemical production, particularly phenolic recovery, higher catalyst loading may be justified despite lower yields due to increased product value. For integrated biorefinery systems, the intermediate condition (≈10 wt.%) offers a balanced approach, enabling simultaneous recovery of liquid fuels, valuable chemicals, and syngas for process heat or synthesis applications. These findings highlight that optimal catalyst loading is application-specific, and that excessive catalyst use may not be economically justified without integrated utilization of gaseous products.

J. Overall Implication

Overall, this study demonstrates that zeolite Y does not merely improve bio-oil quality but fundamentally alters the product distribution and reaction pathway, enabling controlled tuning of pyrolysis outputs. The identification of a catalyst loading threshold (5–10 wt.%) provides a practical guideline for optimizing catalytic pyrolysis processes based on desired product outcomes. This threshold represents the operational window where catalytic benefits deoxygenation, phenolic enrichment, and acid reduction are maximized without incurring the disproportionate liquid-yield penalties associated with higher catalyst fractions. These findings therefore serve as a practical reference for process engineers and researchers seeking to design zeolite-catalyzed pyrolysis systems that are simultaneously effective in bio-oil upgrading and viable in terms of liquid product recovery.

K. Comparative Analysis with Recent Literature

K.1. Comparison of Product Yield Distribution with Recent Studies

The bio-oil yield of 51.85 wt.% obtained under non-catalytic conditions in this study is consistent with the range reported in recent literature for fixed-bed pyrolysis of lignocellulosic biomass. Wang et al. (2022), in a comprehensive review of catalytic pyrolysis of lignocellulosic biomass, confirmed that bio-oil production in non-catalytic fast pyrolysis typically ranges from 40 to 70 wt.%, depending on feedstock composition, temperature, and reactor type. The 51.85 wt.% non-catalytic bio-oil yield for *A. aspera* wood residue falls within this established range, supporting the validity of the experimental protocol. Furthermore, Wang et al. (2022) noted that bio-oil yields in catalytic pyrolysis are consistently lower than in non-catalytic conditions due to deoxygenation reactions a pattern fully corroborated by the present study, where yields declined progressively from 52.95 wt.% (95/5) to 29.45 wt.% (85/15) with increasing zeolite Y loading.

The inverse relationship between catalyst loading and bio-oil yield observed here is strongly validated by Reza et al. (2023b), whose comprehensive review systematically documented that increasing zeolite catalyst proportions across diverse biomass feedstocks consistently reduces liquid product yield while enhancing gas-phase fractions. Their analysis showed that the Brønsted acid sites in zeolite frameworks promote secondary vapor cracking reactions that convert condensable oxygenates into CO, CO_2, and light non-condensable hydrocarbons precisely the mechanism responsible for the syngas increase from 22.40 wt.% to 53.50 wt.% observed in this study. Similarly, Awodun et al. (2025), in a systematic review, confirmed that catalyst-induced secondary cracking in in-situ pyrolysis configurations preferentially directs carbon toward gaseous products, resulting in the liquid yield penalty characteristic of high catalyst-to-biomass ratios.

The slight increase in bio-oil yield at the 95/5 ratio (52.95 wt.%) compared to the non-catalytic baseline (51.85 wt.%) is a noteworthy finding that finds support in recent literature. Sun et al. (2025), in their review of catalytic pyrolysis using zeolite, carbonaceous, and metal oxide catalysts in Nanomaterials, documented that at very low catalyst loadings, zeolite Y and related large-pore zeolites

can marginally improve bio-oil condensation efficiency by promoting selective cracking of high-molecular-weight oxygenates that would otherwise remain in the vapor phase uncondensed. This behavior distinguishes large-pore zeolites (such as zeolite Y with 7.4 Å supercages) from medium-pore zeolites (such as ZSM-5 with 5.5 Å channels), which more aggressively crack primary vapors even at low loadings. A point of partial contrast, however, is noted in the work of Liu et al. (2023), who studied catalytic fast pyrolysis of neem sawdust over ZSM-5 zeolites and found no such preliminary yield increase; instead, even low ZSM-5 loading immediately reduced bio-oil yield. This difference can be attributed to the distinct pore architecture of ZSM-5 versus zeolite Y: the stronger acidity and narrower 10-membered-ring channels of ZSM-5 initiate more aggressive cracking at all loading levels, whereas zeolite Y's larger, more accommodating supercages selectively upgrade heavier fragments without immediately converting all vapors to gases at low loadings.

The progressive decrease in biochar yield from 25.75 wt.% (100/0) to 17.05 wt.% (85/15) observed in this study is consistent with findings across the recent literature. The Sun et al. (2025) review confirmed that increasing zeolite loading reduces char yield by facilitating more complete volatilization of carbonaceous solid intermediates rather than by directly altering primary biomass decomposition. This aligns with the interpretation that zeolite Y in this study primarily acted on the vapor phase rather than the solid matrix. A complementary perspective is offered by the Catalytic Pyrolysis of Biomass review by Sun et al. (2025), which further noted that catalyst-mediated enhancement of volatile evolution can reduce fixed carbon accumulation in the char fraction, consistent with the moderate but steady biochar yield reduction observed across the four loading levels in this study.

K.2. Comparison of Bio-oil Composition and Phenolic Enrichment

The GC–MS-identified increase in phenolic content from 19.95% (non-catalytic) to 33.08% (85/15 ratio) is in strong agreement with the broader literature on zeolite-catalyzed phenolic enrichment. The comprehensive review by Sun et al. (2025) confirmed that zeolite catalysts particularly those with large-pore frameworks such as Y-zeolite consistently enrich phenolic fractions in bio-oil through demethoxylation of lignin-derived guaiacols and syringols and through selective cracking of aliphatic ether linkages. The Sun et al. (2025) review further reported that nanocatalysts yielded nearly half the acid content of bulk catalysts (8.69% vs. 16%), providing direct benchmark support for the 20.64% reduction in carboxylic acids observed in this study. This validates the deoxygenation efficacy of zeolite Y at moderate loadings and confirms that the acid-reduction pattern reported here is reproducible across different feedstock types and catalyst configurations.

The phenolic enrichment pathway identified in this study involving demethoxylation, decarboxylation, and aromatization promoted by zeolite Y's Brønsted acidity is mechanistically corroborated by the work of Venegas-Aasconez et al. (2024), whose study on biomass valorization through catalytic pyrolysis using metal-impregnated natural zeolites demonstrated that acidic sites within zeolite pores facilitate precisely these deoxygenation reactions dehydration, decarboxylation, decarbonylation, aldol condensation, and aromatization to convert oxygenated compounds into aromatic-enriched bio-oils. Analogously, Wang et al. (2022) documented that catalytic pyrolysis of lignocellulosic biomass over zeolite catalysts promoted demethoxylation of lignin fragments as a primary mechanism of phenolic enrichment, consistent with the molecular transformation patterns observed in this study across the four catalyst-loading levels.

An important point of partial contrast merits discussion. The review of biomass pyrolysis over zeolites by Lachos-Perez et al. (2023) reported that Y-zeolite produced a high bio-oil yield of 55.2 wt.% with the highest production of phenolic monomers compared to basic and acidic metal oxide catalysts in rice straw pyrolysis. While the directional trend (zeolite Y favoring phenolics) agrees with the present study, the substantially higher phenolic monomer content in that work likely reflects the higher lignin content of rice straw compared to *A. aspera* wood residue, as well as differences in reactor configuration (fluidized versus fixed bed) and operating conditions. The *A. aspera* feedstock in this study, which has not been previously characterized in the pyrolysis context, appears to yield lower baseline phenolics (19.95% non-

catalytic) than rice straw-derived bio-oils, suggesting that feedstock-specific lignin quantity and the distribution of ether linkages play a significant role in determining the magnitude of phenolic enrichment achievable through zeolite catalysis.

K.3. Catalyst Loading Thresholds and Diminishing Returns

The identification of a catalyst saturation threshold at approximately 5–10 wt.% in this study, beyond which further zeolite Y addition yields diminishing compositional benefits but disproportionate liquid yield losses, is strongly supported by several recent investigations. Reza et al. (2023b) explicitly noted that active acid sites in zeolite catalysts approach saturation at moderate catalyst-to-biomass ratios, after which additional catalyst primarily drives over-cracking to gases rather than selective deoxygenation. A comparable threshold behavior was documented by Wang et al. (2022), who reviewed multiple studies and concluded that the relationship between catalyst loading and bio-oil quality follows a non-linear pattern, with maximum upgrading efficiency achieved at intermediate loadings. The ANOVA results reported in this study, showing statistically significant differences between catalytic and non-catalytic conditions but non-significant differences among the individual catalyst loadings, align with this saturation interpretation and are consistent with similar ANOVA-based findings in recent fixed-bed catalytic pyrolysis literature (Reza et al., 2023b).

A noteworthy contrast is offered by Liu et al. (2023), who found that bio-oil yield and hydrocarbon selectivity during neem sawdust pyrolysis over ZSM-5 continued to improve with increasing catalyst loading up to higher catalyst-to-biomass ratios than those tested in this study, without a clear saturation plateau within the investigated range. This discrepancy is attributable to fundamental differences between ZSM-5 and zeolite Y: ZSM-5 has a higher density of strong Brønsted acid sites and a narrower pore geometry, giving it substantially greater cracking activity per unit mass. As a result, the saturation point for ZSM-5 is reached at higher catalyst-to-biomass ratios than for zeolite Y. In the present study, zeolite Y's more moderate acidity and larger pore size (7.4 Å) apparently leads to acid-site saturation at the 90/10 loading level, which is consistent with the negligible compositional differences observed between the 90/10 and 85/15 conditions. This distinction underscores an important practical implication: zeolite Y may offer superior tunability at low-to-moderate loading levels compared to ZSM-5 for applications where phenolic enrichment rather than maximum deoxygenation to aromatics is the primary objective.

K.4. Deoxygenation Pathways and GC–MS Characterization: Comparison with Recent Work

The deoxygenation pathways identified in this study decarboxylation, decarbonylation, dehydration, and demethoxylation are consistent with those reported in the most recent catalytic pyrolysis literature. Awodun et al. (2025), confirmed that lignin-derived compounds undergo demethoxylation at the Brønsted acid sites of zeolites, releasing methanol and formaldehyde and yielding simpler phenols. This aligns directly with the compound-class evolution observed in this study, where guaiacol- and methoxyphenol-type species diminish with increasing catalyst loading as phenol-type concentrations rise. Concurrently, Wang et al. (2022) documented that decarboxylation reactions at zeolite acid sites convert carboxylic acids to CO_2 and lighter hydrocarbons, consistent with the 20.64% reduction in carboxylic acid content observed from the non-catalytic to the 85/15 condition in this study.

Regarding GC–MS analytical approach, Vilas-Boas et al. (2025), in their methodological review on GC–MS characterization of bio-oils from biomass pyrolysis, confirmed that GC–MS peak-area-based compound class profiling (the approach used in this study) is the most widely adopted method for bio-oil molecular characterization, providing reliable relative trends even when absolute quantification is constrained by the absence of calibration standards. This validates the methodological choice made in this study and situates the GC–MS results within the current best practices for biomass pyrolysis oil characterization. Vilas-Boas et al. (2025) further noted, however, that GC–MS typically captures only 40–70% of the total bio-oil composition, reinforcing the limitation acknowledged in Section 5.0 that the compositional findings represent indicative trends rather than definitive quantitative assessments.

K.5. Practical Feasibility and Biorefinery Context: Alignment with Recent Work

The multi-objective optimization framework developed in this study identifying different optimal catalyst loadings for fuel production (95/5), chemical recovery (85/15), and integrated biorefinery applications (90/10) aligns closely with recent perspectives in the literature. Wang et al. (2022) explicitly argued that the selection of catalyst-to-biomass ratio in lignocellulosic biomass pyrolysis cannot be optimized for a single objective and must be determined by the intended product valorization pathway, supporting the application-specific approach taken in this study. In a techno-economic context, the moderate catalyst requirements (5–10 wt.%) identified as optimal in this study are consistent with the economic feasibility windows described by Reza et al. (2023b), who noted that catalyst loadings below 15 wt.% generally represent the economically practical range for batch and semi-continuous pyrolysis systems, particularly for zeolite catalysts that can be regenerated and reused over multiple cycles.

The large increase in syngas yield at high catalyst loadings observed in this study (53.50 wt.% at 85/15) has significant practical co-product implications that are supported by recent literature. Awodun et al. (2025) highlighted that the elevated gas fractions generated during high-loading catalytic pyrolysis are not simply losses but represent a valorizable stream for on-site heat recovery or Fischer–Tropsch synthesis. This perspective supports the Scenario 3 (integrated biorefinery) framework presented in Section 4.4 of this study and contextualizes the 85/15 condition not as a purely negative outcome but as a process configuration suited to facilities where gas-phase energy recovery offsets liquid yield reduction. The Nanomaterials review by Sun et al. (2025) further noted that the gas fraction from zeolite-catalyzed pyrolysis is typically enriched in CO and light hydrocarbons, which have direct utility as synthesis gas precursors, consistent with the substantial syngas increase observed at the 85/15 condition in this study.

V. CONCLUSION

This study investigated the influence of zeolite Y catalyst loading on product yield distribution and bio-oil molecular composition during the catalytic pyrolysis of Achyranthes aspera wood residue at 500 °C. Experiments conducted across biomass-to-catalyst ratios of 100/0, 95/5, 90/10, and 85/15 (wt.%) demonstrated that catalyst addition fundamentally altered both the carbon distribution among product phases and the molecular composition of the resulting bio-oil, while mean-based linear interpolation provided a rigorous quantitative optimization framework, collectively establishing A. aspera as a technically promising lignocellulosic feedstock for sustainable bio-oil production.

Increasing zeolite Y loading progressively reduced bio-oil yield from 52.95 wt.% (95/5) to 29.45 wt.% (85/15), while syngas production increased sharply from 22.40 wt.% to 53.50 wt.% and biochar yield decreased from 25.75 wt.% to 17.05 wt.%. This pattern reflects a catalyst-induced transition from a liquid-production regime to a gas-generation regime, driven by secondary vapour-phase cracking, decarboxylation, dehydration, and demethoxylation at zeolite Y's Brønsted acid sites. ANOVA ($p < 0.05$) confirmed that differences among product types were statistically significant, validating the measurable catalytic influence on yield distribution. More so, there is a significant difference between the loading ratios.

GC–MS characterization revealed that zeolite Y markedly enriched the phenolic fraction of the bio-oil, which increased from 19.95% (non-catalytic) to 33.08% at the 85/15 ratio, representing a 65.8% relative enhancement, while carboxylic acids declined from 5.28% to 4.19%, a 20.64% reduction. ANOVA ($p < 0.05$) confirmed that these compositional shifts were statistically significant, attributable to catalytic deoxygenation pathways including demethoxylation of lignin-derived compounds, decarboxylation of acidic species, and shape-selective aromatization within zeolite Y's 7.4 Å supercage framework. It is explicitly acknowledged that GC–MS peak-area percentages are semi-quantitative, reflecting relative abundance within the detectable fraction only; conclusions regarding bio-oil quality improvement are therefore appropriately interpreted as indicative compositional trends rather than definitive quantitative measurements, pending comprehensive physicochemical characterization including heating value, viscosity, and elemental analysis.

Mean-based linear interpolation of the product yield data established that the arithmetic means of all three products (bio-oil: 45.25 wt.%; biochar: 21.525 wt.%; syngas: 33.225 wt.%) converge simultaneously within the 90/10–85/15 loading interval, identifying the optimal catalytic loading range as 10–15 wt.% zeolite Y. Applying the interpolation formula to bio-oil yield as the primary optimization variable, the precise optimal catalyst loading value was determined as 10.43 wt.% (biomass-to-catalyst ratio ≈ 89.57/10.43), at which bio-oil yield equals its experimental mean of 45.25 wt.%, biochar yield is 20.93 wt.%, and syngas yield is 33.82 wt.%, summing to 100.00 wt.%. The 90/10 ratio which lies only 0.43 percentage points below this analytically derived optimum represents the most practical experimentally tested operating condition for balanced multi-product output. From an application-specific perspective, the 95/5 ratio maximizes bio-oil yield (52.95 wt.%) for fuel-oriented production; the 85/15 ratio maximizes phenolic content (33.08%) for chemical extraction; and the interpolated optimal value of 10.43 wt.% (approximated by the 90/10 ratio) provides the mean-referenced balanced operating point for integrated biorefinery applications.

The catalytic upgrading mechanism is attributed to zeolite Y's combination of moderate Brønsted acidity and large 7.4 Å supercage pore structure, which facilitates vapour-phase cracking, decarboxylation, demethoxylation, and shape-selective conversion of lignin-derived oligomers into stable aromatic phenolics. Comparison with recent literature (Wang et al., 2022; Reza et al., 2023b; Sun et al., 2025; Awodun et al., 2025) confirms that the yield trends, deoxygenation pathways, catalyst saturation behaviour, and application-specific trade-offs identified in this study are consistent with findings across a broad range of lignocellulosic feedstocks and zeolite-based catalysts, validating the robustness and generalizability of the results.

From a practical standpoint, this research establishes A. aspera wood residue as a technically viable and economically promising feedstock for thermochemical conversion. The phenolic enrichment and acid reduction demonstrated under catalytic conditions enhance the bio-oil's potential for renewable fuel blending, hydrodeoxygenation upgrading, and recovery of high-value phenolic intermediates for resin, adhesive, and pharmaceutical applications. The moderate catalyst requirements of the analytically derived optimum (10.43 wt.%, practically realized as 90/10) are consistent with the economic feasibility windows reported in recent literature and support industrial implementation when integrated with catalyst regeneration strategies. The large syngas fraction produced at higher catalyst loadings (53.50 wt.% at 85/15) further represents a valorizable co-product stream for process heat recovery or Fischer–Tropsch liquid synthesis, partially offsetting the liquid yield reduction at high catalyst ratios.

Nevertheless, several limitations of this study warrant acknowledgment. The experiments were conducted at a single temperature (500 °C) and atmospheric pressure in batch operation, which may not fully predict continuous-reactor performance or account for catalyst deactivation kinetics. In addition, only GC–MS-detectable compounds were characterized while critical fuel properties such as heating value, viscosity, water content, and thermal stability were not presented. It should be explicitly acknowledged that GC–MS peak-area percentages as reported in Table 3 represent relative abundance within the detectable fraction rather than absolute mass yields, and are further subject to compound-specific ionization efficiencies, detector response variation, and the absence of authentic calibration standards for each analyte. Consequently, conclusions regarding "bio-oil quality improvement" are appropriately interpreted as indicative compositional trends rather than definitive quantitative measurements. The observed increases in phenolic peak area and reductions in carboxylic-acid area provide strong evidence of catalytic upgrading directionality; however, they should not be equated with gravimetric concentration increases without supporting absolute-yield or spectroscopic (e.g., FTIR, NMR) data. Future work should complement GC–MS profiling with calibrated external-standard quantification and comprehensive physico-chemical characterization (calorific value, pH, viscosity, water content) to enable robust quality benchmarking against established bio-oil standards. Future research should address these gaps through multi-factorial experimental designs incorporating temperature and pressure variations, continuous-reactor studies with catalyst-regeneration cycles, and comprehensive physicochemical characterization of all pyrolysis products.

In conclusion, this work demonstrates that zeolite Y-catalyzed pyrolysis of A. aspera wood residue yields bio-oil with significantly enhanced phenolic content and reduced acidity relative to non-catalytic conditions, and that mean-based linear interpolation provides a rigorous, data-driven framework for optimization within fixed-point experimental datasets. These findings contribute to the growing knowledge base on catalytic biomass pyrolysis, validate mean-based interpolation as an accessible optimization tool, and establish A. aspera wood residue as a valuable addition to the portfolio of tropical lignocellulosic feedstocks suitable for sustainable bioenergy and biochemical production. Future work should address multi-temperature optimization, continuous-reactor performance, catalyst regeneration kinetics, and comprehensive physicochemical characterization of all pyrolysis products to enable full-scale process design and techno-economic evaluation.

VI. RECOMMENDATİONS

Based on the experimental findings and analytical results of this study, the following recommendations are proposed for future research and practical implementation:

1. Optimization of Catalytic Parameters: Further studies should investigate a broader range of catalyst loadings, particle sizes, and reaction temperatures to determine the precise operating window that maximizes both bio-oil quality and yield. Response Surface Methodology (RSM) or similar statistical optimization techniques can be applied to model these interactions more accurately.

2. Catalyst Modification and Regeneration: The performance of zeolite Y could be enhanced by ion exchange or impregnation with transition metals (e.g., Ni, Co, Fe) to improve its acidity, stability, and deoxygenation capacity. Additionally, the regeneration and reusability of the catalyst should be examined to assess its long-term economic viability for large-scale applications.

3. Comparative Catalytic Studies: Comparative evaluation of zeolite Y with other catalysts such as ZSM-5, H-Beta, and mesoporous aluminosilicates would provide valuable insight into structure–activity relationships and guide the selection of the most effective catalyst for specific feedstocks.

4. Upgrading and Fuel Property Assessment: Further upgrading of the produced bio-oil through hydrodeoxygenation, esterification, or co-processing with petroleum fractions should be conducted to assess improvements in viscosity, calorific value, and storage stability. Comprehensive fuel property evaluation will enable its potential integration into existing fuel systems.

5. Techno-Economic and Environmental Analysis: A full life-cycle assessment (LCA) and economic feasibility study should be undertaken to evaluate the scalability, environmental impact, and sustainability of Achyranthes aspera pyrolysis under catalytic and non-catalytic conditions.

6. Application-Specific Development: Given the high phenolic content observed in the catalytic bio-oil, targeted recovery of phenol derivatives for use in resin, adhesive, or antioxidant production should be explored as a potential value-added pathway.

DECLARATİONS

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. and S.O. 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

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

Awodun K., He Y., Wu C., Soltani S.M. (2025). Catalytic pyrolysis of bio-waste in synthesis of value-added products: A systematic review. *Fuel Processing Technology*, *275*, 1-22. https://doi.org/10.1016/j.fuproc.2025.108258

Bampaou M., Panopoulos K.D., Seferlis P., Voutetakis S. (2022). Evaluation of novel hydrogen integration options in bio-oils introduction to petrochemical refineries. *Energy,. 254*, 1-21. https://doi.org/10.1016/j.energy.2022.124353.

Begum Y.A., Kumari S., Jain S.K., Garg M.C. (2024). A review on waste biomass-to-energy: integrated thermochemical and biochemical conversion for resource recovery. *Environmental Science Advances*, *3*, 1197-1216. https://doi.org/10.1039/d4va00109e.

Castro D.A.R., Ribeiro H.J.S., Guerreiro L.H.H., Bernar L.P., Bremer S.J., Santo M.C., Almeida H.S., Jr S.D., Borges L.E.P., Machado N.T. (2021). Production of fuel-like fractions by fractional distillation of bio-oil from acai (euterpe oleracea mart.) seeds pyrolysis. *Energies*, *14*(13), 1-27. https://doi.org/10.3390/en14133713.

Chan Y.H., Loh S.K., Chin B.L.F., Yiin C.L., How B.S., Cheah K.W., Wong M.K., Loy A.C.M., Gwee Y.L., Lo S.L.Y., Yusup S., Lam S. (2020). Fractionation and Extraction of Bio-Oil for Production of Greener Fuel and Value- Added Chemicals: Recent Advances and Future Prospects. *Chemical Engineering Journal*, *397*, 1-20. https://doi.org/10.1016/j.cej.2020.125406

Chen, W., Shi, S., Zhang, J., Chen, M., & Zhou, X. (2016). Co-pyrolysis of waste newspaper with high-density polyethylene: Synergistic effect and oil characterization. *Energy Conversion and Management*, *112*, 41–48. https://doi.org/10.1016/j.enconman.2016.01.005.

Dhiman P., Dhiman M., Sharma A., Thakur M., Gautam S., Kumar A. (2024). Role of biochar as support material for photo catalytic operation: A review. *Sustainable Chemistry for the Environment*, *8*, 1-22. https://doi.org/10.1016/j.scenv.2024.100174.

Dia L., Zhou N., Li H., Deng W., Cheng Y., Wang Y., Liu Y., Cobb K., Lei H., Chen P., Ruan R. (2020). Recent advances in improving lignocellulosic biomass-based bio-oil production. *Journal of Analytical and Applied Pyrolysis*, *149*, 1-14. https://doi.org/10.1016/j.japp.2020.104835.

Diaz A.C., Abdelouahed L., Brodu N., Montes-Jimenez V., Taouk B. (2024). Upgrading of pyrolysis bio-oil by catalytic hydrodeoxygenation, a review focused on catalysts, model molecules, deactivation, and reaction routes. *Molecules*, *29*(18), 1-42. https://doi.org/10.3390/molecules29184325.

Efeovbokhan V.E., Ayeni A.O., Eduvie O.P., Omoleye J.A., Bolade O.P., Ogunbiyi A.T., Anyakora V.N. (2020). Classification and characterization of bio-oil obtained from catalytic and non-catalytic pyrolysis of desludging sewage sample. *Energy*, *8*(6), 1088-1107. https://doi.org/10.3934/energy.2020.6.1088.

Egbosiuba T.C. (2022). Biochar and boi-oil fuel properties from nickel nanoparticles assisted pyrolysis of cassava peel. *Heliyon*, *8*(8), 1-13. https://doi.org/10.1016/j.heliyon.2022.e10114

El-Araby R. (2024). Biofuel production: Exploring renewable energy solutions for a greener future. *Biotechnology for Biofuels and Bioproducts*, *17*, 1-32. https://doi.org/10.1186/s13068-024-02571-9.

Ganesapillai M., Mehta R., Tiwari A., Sinha A., Baksi H.S., Chellappa V., Drewnowski J. (2023). Waste to energy: A review of biochar production with emphasis on mathematical modelling and its application. *Heliyon*, *9*(4), 1-22. https://doi.org/10.1016/j.heliyon.2023.e14873.

Harussani M.M., Sapuan S.M. (2022). Development of kenaf biochar in engineering and agricultural applications. *Chemistry Africa*, *5*, 1-17. https://doi.org/10.1007/s42250-021-00293-1.

Iisa K., Mukarakate C., French R.J., Agblevor F.A., Santosa D.M., Wang H., Wilson N.A., Christensen E., Griffin M.B., Schaidle J.A. (2023). From biomass to fuel blendstocks via catalytic fast pyrolysis and hydrotreating: An evaluation of carbon efficiency and fuel properties for three pathways. *Energy and Fuel*, *37*(24), 19653-19663. https://doi.org/10.1021/acs.energyfuels.3c03239.

Iliopoulou E.F., Antonakou E.V., Karakoulia S.A., Vasalos I.A., Lappas A.A., Triantafyllidis K.S. (2007). Catalytic conversion of biomass pyrolysis products by mesoporous materials: Effect of steam stability and acidity of Al-MCM-41 catalysts. *Chemical Engineering Journal*, *134*, 51–57. https://10.1016/j.cej.2007.03.066.

Ilyin S., Makarova V.V. (2022). Bio-oil: Production, modification, and application. *Chemical and Technology of Fuels and Oils*, *58*(2022), 29-44. https://doi.org/10.1007/s10553-022-01348-w

Jaiswal K.K., Chowdhury C.R., Yadav D., Verma R., Dutta S., Jaiswal K.S., Karuppasamy K.S.K. (2022). Renewable and sustainable clean energy development and impact on social, economic, and environmental health. *Energy Nexus*, *7*, 1-14. https://doi.org/10.1016/j.nexus.2022.100118.

Jamilatun S., Arifah Z., Mufandi I. (2025). Comparative analysis of product yield and chemical composition in sugarcane bagasse pyrolysis with and without iron catalysis. *International Conference on Engineering and Applied Science (ICEAT), Journal of Physics: Conference Series,* 10 pp. https://doi.org/10.1088/1742-6596/2989/1/012007

Kabakci S.B., Hacibektasoglu S. (2017). Catalytic Pyrolysis of Biomass. In Tech 1-20. https://doi.org/10.5772/67569

Kass M.D., Armstrong B.L., Kaul B.C., Connatser R.M., Lewis S., Keiser J.R., Jun J., Warrington G., Sulejmanovic D. (2020). Stability, combustion, and compatibility of high-viscosity heavey fuel oil blends with a fast pyrolysis-bio-oil. *Energy Fuels*, *34*(7), 8403-8413. https://doi.org/10.1021/acs.energyfuels.0c00721.

Khlifi S., Pozzobon V., Lajili M. (2024). A comprehensive review of syngas production, fuel properties, and operational parameters for biomass conversion. *Energies*, *17*(15), 1-17. https://doi.org/10.3390/en17153646.

Kumar R., Strezov V. (2021). Thermochemical production of bio-oil: A review of downstream processing technologies for bio-oil upgrading, production of hydrogen and high value-added products. *Renewable and Sustainable Energy Reviews*, *135*, 1-15. https://doi.org/10.1016/j.rser.2020.110152.

Lachos-Perez D., Martins-Vieira J.C., Missau J., Anshu K., Siakpebru O.K., Thengane S.K., Morais A.R.C., Tanabe E.H., Bertuol D.A. (2023). Review on biomass pyrolysis with a focus on bio-oil upgrading techniques. *Analytica*, *4*(2), 182-205. https://doi.org/10.3390/analytica4020015.

Li R., Wu Y., Lou H.L., Cheng J., Shen B., Qin L. (2023). Porous biochar materials for sustainable water treatment: Synthesis, modification, and application. *Water*, *15*(3), 1-18. https://doi.org/10.3390/w15030395.

Li S., Tasnady D. (2023). Biochar for soil carbon sequestration: Current knowledge, mechanisms, and future perspectives. *Journal of Carbon Research*, *9*, 1-30. https://doi.org/10.3390/c9030067.

Liaqat S., Sun Z., Zeng Y., Maeda N., Liu J. (2024). Technical challenges and corrosion research progress in bio-crude co-processing. *Chemical Engineering Journal*, *499*, 155981. https://doi.org/10.1016/j.cej.2024.155981.

Lin H., Zhang L., Zhang S., Li Q., Hu X. (2022). Hydrothermal carbonization of cellulose in aqueous phase of bio-oil: The significant impacts on properties of hydrochar. *Fuel*, *315*, 1-15. https://doi.org/10.1016/j.fuel.2022.123132.

Liu N.R., Rahman M.M., Sarker M., Chai M., Li C., Cai J. (2020). A review on the catalytic pyrolysis of biomass for the bio-oil production with ZSM-5: Focus on structure. *Fuel Processing Technology*, *199*, 1-22. https://doi.org/10.1016/j.fuproc.2019.106301.

Liu, J., Xue, X., Wu, L., Liang, J. (2023). Production of bio-oils from the catalytic pyrolysis of neem sawdust: Comparative study of versatile zeolite parameters. *Fuel Processing Technology*, *247*, 107808. https://doi.org/10.1016/j.fuproc.2023.107808.

Machado H., Cristino A.F., Oriskova S., Santos R.G. (2022). Bio-Oil: The next-generation source of chemicals. *Reactions*, *3*, 118-137. https://doi.org/10.3390/reactions3010009.

Mahmud M.N., Muniza N.T., Ahmed A. (2025). Low-cost biochar: A Sustainable approach to improve soil fertility and crop yield for small-scale farmers. *American Journal of Environmental Economics (AJEE)*, *4*(1), 67-72. https://doi.org/10.54536/ajee.v4i1.4613

Mante O.D., Agblevor F.A., McClung R. (2013). A Study on Catalytic pyrolysis of biomass with Y-Zeolite based FCC catalyst using response surface methodology. *Fuel*, *108*, 1-23. https://doi.org/10.1016/j.fuel.2012.12.027.

Mignogna D., Szabo M., Ceci P., Avino P. (2024). Biomass energy and biofuels: Perspective, potentials, and challenges in the energy transition. *Sustainability*, *16*(16), 1-25. https://doi.org/10.3390/su16167036.

Motta I.L., Marchesan A.N., Filho R.M., Maciel M.R.W. (2025). Syngas cleaning and conditioning in biomass gasification plants: A review of technologies, bibliometric trends, and future directions. *International Journal of Hydrogen Energy*, *154*, 1-22. https://doi.org/10.1016/j.ijhydene.2025.150234.

Nanda S., Pattnaik F., Borugadda V.B., Dalai A.K., Kozinski J.A., Naik S. (2021). Catalytic and noncatalytic upgrading of bio-oil to synthetic fuels: An introductory review. *American Chemistry Society Symposium Series*, 1-28. https://doi.org/10.1021/bk-2021-1379.ch001.

Nguyen T.B.N, Le N.V.L. (2023). Biomass resources and thermal conversion biomass to biofuel for cleaner energy: A review. *Journal of Emerging Science and Engineering*, *1*(1), 6-13. https://doi.org/10.61435/jese.2023.2.

Osanyinpeju K.L., Aderinlewo A.A., Adetunji O.R., E.S.A. Ajisegiri (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., E.S.A. Ajisegiri (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.

Oyebanji, J. A., Fayomi, O. S. I., Oyeniyi, O. I., Akor, P. G., Ajayi, S. T. (2022). Physico-chemical analysis of pyrolyzed bio-oil from Lophiraalata (ironwood) wood, *Journal of Environmental Pollution and Management, 4*, 101.

Oyebanji, J. A., Obinna, J. P., and Oyebanji, O. T. (2023a). 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., and Fayomi, O. S. I. (2020). Synthesis and characterization of zeolite-Y using Ficus exasperata leaf: A preliminary study. *Case Studies in Chemical and Environmental Engineering*, *2*, 100063.

Oyebanji, J. A., Okekunle, P. O., and Itabiyi, O. E. (2023b). Box Behnken design application for optimization of bio-oil yield from catalytic pyrolysis of agro-residue. *Fuel Communications*, 100091.

Oyebanji, J. A., Okekunle, P. O., Oyedepo, S. O., and Fayomi, O. S. I. (2021a). characterization of liquid and solid products from pyrolysis of terminalia ivorensis. *IOP Conference Series: Materials Science and Engineering*, *1107*(1) 012127.

Oyebanji, J. A., Okekunle, P. O., Oyedepo, S. O., and Fayomi, O. S.I (2021b). Physicochemical properties of wood sawdust: A preliminary study. *IOP Conference Series: Materials Science and Engineering*, *1107*(1), 012125, 2021

Oyebanji, J. A., Oyedepo, S. O., Okekunle, P. O., lasode, O. A and Adekeye. T. (2018a). Product yield distribution and essential oil composition of eucalyptus terminalis sawdust pyrolysis. *IOP Conf. Series: Materials Science and Engineering*, *391*.

Oyebanji, J. A., Okekunle, P.O., Lasode, O.A. and Oyedepo, S.O. (2018b). Chemical composition of bio-oils produced by fast pyrolysis of two energy biomass, *Biofuels*, *9*(4), 479 – 487.

Oyebanji,J. A., Oyedepo, S. O., Oyebanji, O. T., Araoyinbo, A. O., Kilanko, O., Dirisu, J. O., Saleh, B (2023c) Experimental investigation of heating values and chemical compositions of selected fuel woods as bio-fuel sources in developing countries. *Fuel*, *340*, 127600, ISSN 0016-2361.

Panwar L.N., Paul A.S. (2020). An overview of recent development in bio-oil upgrading and separation techniques. *Environmental Engineering Research*, *26*(5), 1-14. https://doi.org/10.4491/eer.2020.382.

Pattiya A., Titiloye J.O., Bridgwater A.V. (2008). Fast pyrolysis of cassava rhizome in the presence of catalysts. *Journal of Analytical and Applied Pyrolysis*, *81*(1), 72-79. https://doi.org/10.1016/j.jaap.2007.09.00.

Pehlivan E. (2023). Non-catalytic and catalytic conversion of fruit waste to synthetic liquid fuel via pyrolysis. *Processes*, *11*(9), 1-20. https://doi.org/10.3390/pr11092536.

Ratnasari D.K. (2021). Enhanced Catalytic Pyrolysis of Biomass for High-Quality Biofuel Production. PhD Thesis, Materials Science and Engineering, KTH Royal Institute of Technology, Stockholm, Sweden 112 pp.

Resende, F. L. (2016). Recent advances on fast hydropyrolysis of biomass. *Catalysis Today*, *269*, 148–155. https://doi.org/10.1016/j.cattod.2016.01.004.

Rey J.R.C., Longo A., Rijo B., Pedrero C.M., Tarelho L.A.C., Brito P.S.D., Nobre C. (2024). A Review of cleaning technologies for biomass-derived syngas. *Fuel*, *377*, 1-28. https://doi.org/10.1016/j.fuel.2024.132776.

Reza M.S., Baktybaevna Iskakova Z.B., Afroze S., Kuterbekov K., Kabyshev A., Bekmyrza K.Z., Kubenova M.M., Bakar M.S.A., Azad A.K., Roy H., Islam M.S. (2023b). Influence of catalyst on the yield and quality of bio-oil for the catalytic pyrolysis of biomass: a comprehensive review. *Energies*, 16(14), 1-39. https://doi.org/10.3390/en16145547.

Reza M.S., Yun C.S., Afroza S., Radenahmad N., Abu M.S., Saidur R., Taweekun J., Azad A.K. (2020). Preparation of activated carbon from biomass and its' application in water and gas purification, a review. *Arab Journal of Basic and Applied Sciences. 27*(1), 208-238. https://doi.org/10.1080/25765299.2020.1766799.

Reza M.S.; Afroze S.; Kuterbekov K.; Kabyshev A.; Bekmyrza K.Z.; Taweekun J.; Ja'afar F.; Bakar M.S.A.; Azad A.K.; Roy H.; Islam M.S. (2023a). Ex Situ Catalytic Pyrolysis of Invasive Pennisetum Purpureum Grass with Activated Carbon for Upgrading Bio-Oil. *Sustainability*, *15*, 1-20. https://doi.org/10.3390/su15097628.

Reza, M.S., Iskakova, Z.B., Afroze, S., Kuterbekov, K., Kabyshev, A., Bekmyrza, K.Z., Kubenova, M.M., Bakar, M.S.A., Azad, A.K., Roy, H., Islam, M.S. (2023b). Influence of Catalyst on the Yield and Quality of Bio-Oil for the Catalytic Pyrolysis of Biomass: A Comprehensive Review. *Energies*, *16*, 5547. https://doi.org/10.3390/en16145547.

Rollag S.A., Lindstrom J.K., Peterson C.A., Brown R.C. (2022). *Chemical Engineering Journal*, *427*, 1-123.

Samolada M.C., Papafotica A., Vasalos I.A. (2000). Catalyst Evaluation for Catalytic Biomass Pyrolysis. *Energy and Fuel*, *14*(6), 1161-1167. https://doi.org/10.1021/ef000026b.

Sanchez-Borrego F.J., Alvarez-Mateos P., Garcia-Martin J.F. (2021). Biodiesel and Other Value-Added Products from Bio-Oil Obtained from Agrifood Waste. *Processes*, *9*, 1-15. https://doi.org/10.3390/pr9050787.

Sayed S.A. (2025). Chemical products yielded from different pyrolysis processes of rice waste residue: A comprehensive review. *Biomass Conversion and Biorefinery*, *15*, 20615-20655. https://doi.org/10.1007/s13399-025-06624-3.

Shahbaz M., AlNouss A., Ghiat I., Mckay G., Mackey H., Elkhalifa S., Al-Ansari T. (2021). A comprehensive review of biomass based thermochemical conversion technologies integrated with CO_2 capture and utilisation within BECCS Networks. *Resources, Conversion and Recycling*, *173*(2021), 1-25. https://doi.org/10.1016/j.rescorec.2021.105734.

Shahbeik H., Shafizadeh A., Gupta V.K., Lam S.S., Rastegari H., Peng W., Pan J., Tabatabaei M., Aghbashlo M. (2023). Using nanocatalysts to upgrade pyrolysis bio-oil: A critical review. *Journal of Cleaner Production*, *413*, 1-13. https://doi.org/10.1016/j.jclepro.2023.137473.

Shoudho K.N., Khan T.H., Ara U.R., Khan M.R., Shawon Z.B.Z., Hoque M.E. (2024). Biochar in global carbon cycle: Towards sustainable development goals. *Current Research in Green and Sustainable Chemistry*, *8*, 1-17. https://doi.org/10.1016/j.crgsc.2024.100409.

Stelmach S., Ignasiak K., Czardybon A., Bigda J., (2023). Evaluation of bio-oils in terms of fuel properties. *Processes*, *11*(12), 1-12. https://doi.org/10.3390/pr11123317.

Sun W., Yan Y., Wei Y., Ma J., Niu Z., Hu G. (2025). Catalytic pyrolysis of biomass: A Review of zeolite, carbonaceous, and metal oxide catalysts. *Nanomaterials*, *15*(7), 1-22. https://doi.org/10.3390/nano15070493.

Tursi A. (2019). A Review on biomass: Importance, chemistry, classification, and conversion. *Biofuel Research Journal*, *22*(2019), 962-979. https://doi.org/10.18331/BRJ2019.6.2.3.

Valle B., Palos R., Bilbao J., Gayubo A.G. (2022). Role of zeolite properties in bio-oil deoxygenation and hydrocarbons production by catalytic cracking. *Fuel Processing Technology*, *227*, 1-13. https://doi.org/10.1016/j.fuproc.2021.107130.

Venegas-Vasconez D., Orejuela-Escobar L., Valarezo-Garces A., Guerrero V.H., Tipanluisa-Sarchi L. (2024). Biomass valorization through catalytic pyrolysis using metal-impregnated natural zeolites: From waste to resources. *Polymers*, *16*, 1-18. https://doi.org/10.3390/polym16131912.

Vilas-Boas A.C.M., Tarelho L.A.C., Moura J.M.O., Gomes H.G.M.F., Marques C.C., Pio D.T., Nunes M.I.S., Silvestre A.J.D. (2025). Methodologies for bio-oil characterization from biomass pyrolysis: A review focused on GC-MS. *Journal of Analytical and Applied Pyrolysis*, *185*, 1-20. https://doi.org/10.1016/j.jaap.2024.106850.

Wang Y., Akbarzadeh A., Chong L., Du J., Tahir N., Awasthi M.K. (2022). Catalytic pyrolysis of lignocellulosic biomass for bio-oil production: A review. *Chemosphere*, *297*, 1-21. https://doi.org/10.1016/j.chemosphere.2022.134181 .

Wang Z., Liu S., Lin W., Song W. (2015). Influence of the Zeolite ZSM-5 on Catalytic Pyrolysis of Biomass via TG-FTIR. *BioResources*, *10*(3), 4485-4497. https://bioresources.cnr.ncsu.edu/wp.

Wang, Y., Akbarzadeh, A., Chong, L., Du, J., Tahir, N., Awasthi, M.K. (2022). Catalytic pyrolysis of lignocellulosic biomass for bio-oil production: A review. *Chemosphere*, *297*, 134181. https://doi.org/10.1016/j.chemosphere.2022.134181.

Xu H., Lv S., Wu W., Gao W., Tahir M.H., Guo X., Zhang S. (2025). Catalytic conversion of the heavy fraction of bio-oil into phenol-rich oils using an Fe-Carbon catalyst during straw pyrolysis. *Journal of Analytical and Applied Pyrolysis*, *186*, 1-26. https://doi.org/10.1016/j.jaap.2024.106902.

Yadav S.P.S., Bhandari S., Bhatta D., Poudel A., Bhattarai S., Yadav P., Ghimire N., Paudel P., Paudel P., Shrestha J., Oli B. (2023). Biochar application: A sustainable approach to improve soil health. *Journal of Agriculture and Food Research*, *11*, 1-13. https://doi.org/10.1016/j.jafr.2023.100498.

Yilbasi Z. (2025). Biofuels, e-fuels, and waste-derived fuels: Advances, challenges, and future directions. *Sustainability*, *17*(13), 1-62. https://doi.org/10.3390/su17136145.

Yogalakshmi K.N., Poornima D.T., Sivashanmugam P., Kavitha S., Yukesh K.R., Varjani S., Adishkumar S., Kumar G., Rajesh B.J. (2022). Lignocellulosic biomass-based pyrolysis: A comprehensive review. *Chemosphere*, *286*(2), 1-20. https://doi.org/10.1016/j.chemosphere.2021.131824.

Zhang S., Wang J., Zhu S., Liu X., Xiong Y., Zhang H. (2020). Effect of $MgCl_2$ loading on catalytic pyrolysis of sawdust for bio-oil and mgo-impregnated biochar production. *Journal of Analytical and Applied Pyrolysis*, *152*, 1-24. https://doi.org/10.1016/j.jaap.2020.104962.

Zheng J., Zhu Y., Sun G., Dong Y., Zhu M. (2022). Bio-oil gasification for production of the raw gas as ammonia syngas. *Fuel*, *327*, 1-25. https://doi.org/10.1016/j.fuel.2022.125029

Zhou L., Yang H., Wu H., Wang M., Cheng D. (2013). Catalytic pyrolysis of rice husk by mixing with zinc oxide: characterization of bio-oil and its rheological behavior. *Fuel Processing Technology*, *106*, 385-391. https://doi.org/10.1016/j.fuproc.2012.09.003.

Zhu X., Shi Z., Zhu X., Lai Y., Ma J., Xia A., Huang Y., Liao Q. (2022). Catalytic pyrolysis of biomass with thermal treatment products of spent lithium-ion batteries for the upgrading of bio-oil and syngas. *Fuel*, *326*, 1-23. hcttps://doi.org/10.1016/j.fuel.2022.125018