

Locust Beans Pod as Feedstock for Pyrolysis: Physicochemical and Thermal Characterization

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Abstract

The growing demand for sustainable energy sources and effective agricultural waste management has increased interest in the utilization of lignocellulosic biomass for thermochemical conversion processes. This study evaluates the suitability of African locust bean pod as a potential feedstock for pyrolysis through comprehensive physicochemical and thermal characterization. Proximate analysis revealed a moisture content of 5.5 wt%, volatile matter content of 76 wt%, ash content of 13 wt%, and fixed carbon content of 11 wt%, indicating favourable characteristics for thermal conversion. Fourier Transform Infrared (FTIR) spectroscopy identified the presence of hydroxyl, aliphatic C–H, carbonyl, aromatic, and ether functional groups associated with cellulose, hemicellulose, and lignin structures. Thermogravimetric Analysis (TGA) and Differential Thermal Analysis (DTA) demonstrated a three-stage degradation pattern, with the primary decomposition occurring between 200 and 400°C and a maximum degradation rate observed within the temperature range of 350–380°C. The thermal behaviour confirmed that the major devolatilization process occurs within the temperature range commonly employed for pyrolysis operations. The combined physicochemical and thermal characterization results establish locust bean pod as a promising lignocellulosic biomass feedstock for pyrolysis, with significant potential for bio-oil production, agricultural waste valorization, and renewable energy generation. The findings provide essential baseline data for process optimization, reactor design, and future bioenergy applications involving locust bean pod biomass.

Keywords: Locust Bean Pod, Pyrolysis, Biomass Characterization, FTIR, Thermogravimetric Analysis, Differential Thermal Analysis, Bio-Oil, Renewable Energy.

Introduction

The increasing global adoption of renewable energy in recent decades signifies a significant transformation in power generation, reflecting a collective transition toward more sustainable energy sources. This shift is supported by information from the International Renewable Energy Agency (IRENA), revealing a substantial rise in renewable energy capacity, doubling since 2010. This serves as a clear indication of the growing feasibility and acceptance of renewable energy (IRENA, 2025). Among these, bioenergy stands out as a renewable energy source, as each new crop or harvest represents a partial regeneration of

its resource base, contributing to its sustainability as a fuel. Bioenergy is a general term encompassing substances derived from flowering plants or animal dung (a processed form of plant matter) (Siwal *et al.*, 2020). Biomass primarily originates from trees, crops, algae, and extends to organic wastes on a broader scale, including municipal sludge and kitchen waste. Various biomass processing methods are employed which includes pyrolysis, torrefaction, transesterification, hydrothermal liquefaction (HTL), carbonization, and gasification (Ni *et al.*, 2022).

Biomass residues from agro-industrial processing represent a low-cost, renewable feedstock for thermochemical conversion technologies. Among these residues, the pod of African locust bean (*Parkia biglobosa*) is generated in large quantities during the production of fermented condiment “dawadawa/iru” across West Africa. Traditionally discarded or used as low-value animal feed, the pod accounts for approximately 40–50% of the fruit weight and constitutes an underutilized lignocellulosic waste stream (Oso, 2023). Locust bean is widely cultivated across west Africa for its seeds, which are processed into traditional food condiments. The pods generated during processing are discarded or burned, causing environmental concerns while representing a potential source of renewable source of energy. Despite the availability of locust bean pod, there is limited information exist regarding the physicochemical properties as a feedstock for pyrolysis. Furthermore, there is scarcity of recent studies providing comprehensive characterization data necessary for predicting its thermal degradation behaviour and conversion potential. Addressing this knowledge gap is important for promoting the sustainable utilization of agricultural residues and expanding the portfolio of indigenous biomass resources suitable for renewable energy production.

Problem Statement

The increasing global demand for sustainable energy and environmentally friendly waste management strategies has intensified research into the utilization of agricultural residues as renewable energy resources. In Nigeria and other West African countries, African locust bean (*Parkia biglobosa*) is extensively processed for the production of traditional condiments such as *dawadawa* and *iru*. This processing generates large quantities of locust bean pods, which are often discarded, openly burned, or left to decompose, resulting in environmental pollution and underutilization of a potentially valuable biomass resource.

Aim and Objectives

This study investigates the physicochemical and thermal characteristics of African locust bean pod biomass and determine its suitability as a feedstock for pyrolysis-based bioenergy production with the following objectives:

1. To determine the proximate composition of locust bean pod, including moisture content, volatile matter, ash content, and fixed carbon.

2. To identify the major functional groups and chemical constituents present in locust bean pod using Fourier Transform Infrared (FTIR) spectroscopy.
3. To investigate the thermal degradation behavior and thermal stability of locust bean pod using Thermogravimetric Analysis (TGA) and Differential Thermal Analyses (DTA).

Literature Review

Biomass

Biomass refers to organic material derived from living organisms like plants and animals. Common biomass sources for energy production include plants, wood, and various waste products. This renewable energy source can be converted into usable energy through direct or indirect methods. Direct methods involve burning biomass to generate heat, while indirect methods include processing biomass into biofuels. Various techniques, such as direct firing, co-firing, pyrolysis, gasification, and anaerobic decomposition, are employed to produce different forms of energy. Thermal conversion plays a crucial role in these processes, involving the application of heat to biomass feedstock for purposes like burning, dehydration, or stabilization (Tawfeeq, 2021). Biomass stands out as a distinctive and renewable source of carbon on Earth, offering advantages such as abundance, carbon neutrality, widespread availability, and cost-effectiveness when compared to fossil resources. The exploration and utilization of biomass hold the potential to alleviate the dual challenges posed by the depletion of fossil resources and environmental pollution. Fast pyrolysis emerges as a highly promising technology for biomass utilization due to its straightforward equipment, easily manageable operational conditions, and versatility in adapting to various biomass resources (Zhang *et al.*, 2024). The swift expansion of the world's population and industrial activities has resulted in the extensive utilization of traditional fossil fuels like coal, natural gas, and crude oil. This has given rise to a range of environmental problems, including global warming, climate change, and air pollution. In response to the environmental challenges linked to the consumption of fossil fuels, researchers are actively investigating renewable energy sources and clean technologies for energy conversion (Shafizadeh *et al.*, 2024). Global warming stands as the most significant threat currently confronting humanity. Recent data indicates that an average temperature increase of 2 °C could result in the death of one hundred million people and the extinction of millions of plant and animal species. The Intergovernmental Panel on Climate Change (IPCC), in its fourth assessment report from 2007 and the special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems released in 2019, affirms with a high level of certainty that the intensified warming observed over the last 50 years is primarily attributable to the significant emissions of greenhouse gases (GHGs), including carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) (Antar *et al.*, 2021).

Currently, there are various methods and technologies available for the storage, transformation, or augmentation of energy. Energy can be broadly categorized into two main forms: finite resources (such as coal, petroleum, uranium, and natural gas) and renewable resources (including solar, wind, bioenergy, tidal, and ocean thermal energy). Among these, bioenergy stands out as a renewable energy source, as each new crop or harvest represents a partial regeneration of its resource base, contributing to its sustainability as a fuel. Bioenergy is a general term encompassing substances derived from flowering plants or animal dung (a processed form of plant matter). Essentially, any organic material that has stored sunlight through the process of chemical energy can be classified as biomass (Siwal *et al.*, 2020). The composition of biomass plays a crucial role in influencing the behavior of biomass pyrolysis. Lignocellulose, a primary component, consists mainly of cellulose (40–50 wt.%), hemicellulose (20–40 wt.%), and lignin (20–30 wt.%) [88]. Cellulose constitutes the primary element of the plant structure, with hemicellulose coiling around cellulose fibers, while lignin envelops both cellulose and hemicellulose on the exterior (Liu *et al.*, 2023).

Locust Beans

The African locust bean is a leguminous tree that thrives in various regions, including West Africa, southeast Asia, and tropical South America. Typically, it grows as a medium-sized tree in open savanna woodlands, often standing alone as the sole tree species in a given area. Recognizable for its elongated pods, which cluster together, the immature fruit starts as green and transitions to brown as it matures. The mature pod consists of a husk that encloses a powdery yellow substance, within which dark brown seeds are embedded. The seeds contribute approximately 25.4% of the weight of the dry pod. Analyzing the whole fruit on a dry matter basis reveals a composition of 12.7% protein, 6.8% fat, 6.2% ash, and 18% fiber. In the mature seed, digestible carbohydrates (starch and sugars) account for about 30%, with protein at 30%, fat at 20%, crude fiber at 9%, and minerals at 5%. Notably, the fat content, primarily composed of unsaturated fatty acids (54% of total fatty acids), surpasses that of most grain legumes. The unsaturated fatty acids include linoleic acid (42.5% of total), oleic acid (8.8% of total), and palmitoleic acid (2.7% of total). The saturated fatty acids, contributing 46% of total fatty acids, consist of palmitic acid (31% of total), stearic acid (7.7% of total), arachidic acid (4.2% of total), and behenic acid (3.1% of total) (Uwaegbute, 1996).

In northern Nigeria, the yearly seed production of African Locust beans is estimated to be around 200,000 tonnes. The African Locust Bean (*Parkia biglobosa*) is primarily known for producing the native condiment called "iru" among the Yoruba-speaking people of Nigeria. While its common use is as a condiment, ongoing research aims to explore the diverse benefits of this legume, leading to a review of existing literature for its various applications. Ethnobotanical reports indicate its use as a genital wash for treating urinary tract infections, as a supplement in infant food formulas, as a mosquito repellent, a means of managing

obesity, and a treatment for asthma. Scientific investigations have explored its antibacterial, probiotic, hepatoprotective, antidiabetic, anti-inflammatory, and wound-healing properties, as well as its antihypertensive effects, role as a binder and thickener, and potential as a pesticide and herbicide. Advancements in process technology, new product development, value chain addition, and marketing efforts hold the promise of bringing *P. biglobosa* and other underutilized legumes on par with major global crops (Ikhimalo, 2019).

Rural residents in developing nations like Nigeria often face challenges in affording animal products, which are valuable protein sources due to their high costs or limited availability. As a result, staple diets primarily rely on cereal grains or starchy roots and tuber crops, contributing to health issues associated with protein and vitamin/mineral deficiencies. In the quest for alternatives to animal-based protein and vitamins, the African locust bean (*Parkia biglobosa*) has gained popularity, particularly in its fermented form known as 'dawadawa.' However, the less explored yellow dry powdery fruit pulp, referred to as 'Dorowa' in Hausa, has not received much attention. Many researchers have not extensively investigated its potential uses and benefits (Gernah *et al.*, 2007).

The locust bean tree (*Parkia biglobosa*) is recognized as a valuable economic tree in the savanna tropical regions worldwide. In contrast, termites pose a significant threat as highly destructive insect pests, causing extensive damage to wooden structures, furniture, books, utility poles, and various agricultural crops including sugar cane, millet, barley, cotton, wheat, and paddy. Termites are eurytopic, distributed globally, and exhibit a preference for feeding on cellulose and lignocellulose. In the tropics, they play a crucial role in processing 50-100% of dead plant matter and decaying biomass. The damage inflicted by termite results from their feeding activities, facilitated by symbiotic microbes like bacteria and fungi with the capability to digest cellulose (Muhammad *et al.*, 2023).

Pyrolysis

Pyrolysis, an evolving thermochemical method, employs a variety of biomasses to produce char or bio-crude. This process, also known as dry pyrolysis, involves the decomposition of biomass at exceptionally high temperatures in the absence of oxygen and under atmospheric pressure. The outcome comprises solid (bio-char), liquid (bio-oil), and gaseous (syngas) products (Brindhadevi *et al.*, 2021). It is a transformative process that converts organic materials into gaseous components, a solid residue containing carbon and ash, and a liquid known as pyrolytic oil or bio-oil. It serves as a valuable method for eliminating contaminants from substances through two primary approaches: destruction and removal. In the destruction process, organic contaminants undergo breakdown into compounds with lower molecular weights, while in the removal process, contaminants are not destroyed but are separated from the material. Pyrolysis is particularly effective in treating organic materials prone to "cracking" or decomposition under heat, such as polychlorinated biphenyls (PCBs), dioxins, and polycyclic aromatic hydrocarbons (PAHs) (Boslaugh, 2023).

In contrast to combustion and gasification, pyrolysis boasts reduced emissions, cost-effectiveness, and simplified operational processes (Mumbach *et al.*, 2022).

The transformation of biomass into valuable biofuels is attainable through biochemical, chemical, and thermochemical methods. In contrast to chemical and biochemical methods, thermochemical processes offer greater adaptability in terms of feedstock choice, operating conditions, and the distribution of end products (Terry *et al.*, 2021). Various methods, including pyrolysis, liquefaction, and gasification, can be employed to convert non-food biomass into advanced biofuels. Of these, pyrolysis emerges as the most effective process for directly producing liquid biofuels, the presently predominant form of transportation fuels (Staš *et al.*, 2020).

Fast Pyrolysis

The fast pyrolysis of biomass has demonstrated effectiveness in the production of liquid bio-oil for centralized biorefineries. Typically conducted in an inert or non-oxidative atmosphere, the entire process is endothermic, necessitating external heat input to sustain the pyrolysis reactions at elevated temperatures. The core component of biomass fast pyrolysis technology is the pyrolysis reactor, and the method employed for heat supply is a critical consideration during scaling up. Currently, the primary heat supply methods involve gas/solid heat carriers or heat transfer between the pyrolysis reactor wall and biomass particles. However, practical challenges persist in these approaches, including complex heat transfer systems, operational stability difficulties, and suboptimal heat transfer efficiency (Hu *et al.*, 2022). Fast pyrolysis is recognized as a highly promising thermochemical method for the effective conversion of lignocellulosic biomass. Typically conducted at moderate temperatures (approximately 500°C) and featuring an exceptionally rapid heating rate in an oxygen-free environment, this process results in the decomposition of lignocellulosic biomass, primarily yielding liquid products. A certain quantity of pyrolysis char and gas is also produced in the course of fast pyrolysis (Li *et al.*, 2023). This process occurs in the absence of oxygen, at temperatures ranging from 400 to 600°C, and with a vapor residence time of 0.5 to 3 seconds. The resulting bio-oil can be directly applied, or upgraded to create substances suitable for use as transportation fuels in conventional crude oil refineries.

Flash Pyrolysis

Flash pyrolysis represents a thermal technique where the biomass feedstock, such as wood or straw, undergoes rapid heating with a residence time typically ranging from 0.5 to 3 seconds. This process occurs in the absence of air, and the resulting products are swiftly cooled and condensed, resulting in the formation of a brown liquid. This approach is characterized by its efficiency in rapidly transforming biomass into a condensed liquid product, demonstrating its potential as a versatile and time-efficient method for bio-oil production (Li *et al.*, 2013). Under optimized conditions, the yields of flash pyrolysis oil can

reach levels between 60% and 75% by weight. Effective implementation of the process requires maintaining temperature, heating rate, and residence time within the specified range of 450–600 °C, [Math Processing Error] °C/s, and less than 1 second, respectively. Flash pyrolysis oil is identified by its elevated water content, typically exceeding 15% by weight. The primary pyrolysis products derived from the lignin portion of biomass are phenols (Ighalo *et al.*, 2022). Optimizing the production of liquid bio-oil involves employing elevated heating rates, maintaining moderate temperatures, and ensuring short gas residence times. In contrast, higher temperatures and longer residence times tend to promote increased gas yields. Furthermore, a deliberate strategy of slow heating at lower temperatures has been observed to enhance char yields in the pyrolysis process. Fine-tuning these parameters allows for the strategic manipulation of product distribution during biomass conversion, tailoring the outcomes based on the desired end-products such as liquid bio-oil, gas, or char (Stefan *et al.*, 2021).

Intermediate Pyrolysis

Intermediate pyrolysis is advantageous due to its well-balanced product distribution, making it suitable for the simultaneous production of biochar, bio-oil, and gas. Unlike other methods, intermediate pyrolysis exhibits flexibility in processing various materials and achieves a favorable distribution of products, including easily separable two-phase bio-oil and high-quality, dry biochar (Kazawadi *et al.*, 2021). Intermediate pyrolysis, involving moderate heating rates (100–500 K/min), leads to thermal decomposition in the absence of oxygen and at elevated temperatures (400–600 °C). This process yields a range of products, including liquid substances like bio-oil or pyrolytic oil, carbon-rich solid residues such as biochar, and gaseous by-products. Bio-oil, a highly promising biofuel, can be utilized for heating, power generation, combined heat and power generation, or as a precursor for the production of various chemicals and fuels (Bouaïk *et al.*, 2021). Intermediate pyrolysis presents itself as a viable alternative to both fast and slow pyrolysis methods. In contrast to slow pyrolysis, which is known for its low heating rate leading to the predominant formation of biochar as the primary product, and fast pyrolysis, where high sample heating rates (around 1000 K/s) maximize bio-oil production, intermediate pyrolysis utilizes moderate heating rates (ranging from 100 to 500 K/min). This intermediate heating rate facilitates a balanced production of approximately 40 wt% of char and 40 wt% of bio-oil (Jerzak *et al.*, 2022).

Slow Pyrolysis

Slow pyrolysis, characterized by extended durations that can span several days, is typically executed at relatively modest temperatures, not surpassing 500 °C, and gradual heating rates ranging from 0.1 to 2 °C per second. In slow pyrolysis, the primary products are char and tar, attributed to the prolonged residence time within the pyrolytic converter, facilitating repolymerization and recombination reactions. The composition of char, tar,

and gas produced is also influenced by the specific biomass used. Contemporary industrial applications of slow pyrolysis are focused on biochar production, utilizing the concurrently generated bio-oil and biogas as an energy source for the pyrolytic process. Additionally, valuable chemicals such as acetone, methanol, and acetic acid are extracted from the products of slow pyrolysis (Tamer *et al.*, 2020). Nevertheless, slow pyrolysis encounters various technological limitations that render it unsuitable for generating high-quality bio-oil. The extended residence time leads to significant cracking of the primary product, potentially adversely impacting both the quantity and quality of the bio-oil produced. Furthermore, substantial energy input is necessitated due to the extended residence times and constrained heat transfer (Aboelela *et al.*, 2023).

Bio-oil

Bio-oil, derived as a liquid byproduct from pyrolysis, stands out as a highly promising biofuel for the foreseeable future, including bio-diesel, bio-ethanol, and bio-oil, due to its carbon-neutral characteristics. The utilization of bio-oil results in reduced emissions of sulfur dioxide and nitrogen dioxide compared to conventional fossil fuels. Moreover, the storage and transportation of bio-oil are more convenient when compared to biochar and biogas, as it aligns well with existing equipment, pumping systems, and safety standards (Terry *et al.*, 2021). Various methods, such as pyrolysis, liquefaction, and gasification, can be employed to transform non-food biomass into advanced biofuels. Bio-oils, with suitable enhancements, show significant promise for extensive utilization as second-generation biofuels in both mobile and stationary applications, or as a precursor for various oxygen-containing chemicals. Presently, several countries, such as Finland and the Netherlands, have successfully produced bio-oils on a commercial scale, primarily for applications in biofuels for district heating (Staš *et al.*, 2020).

Bio-oil is chemically intricate and chemically unstable, comprising numerous unsaturated components that necessitate upgrading and refining through thermal reactions. When subjected to heat, the constituents within bio-oil undergo polymerization via free radical reactions, resulting in the formation of solid carbonaceous materials known as coke (Ma *et al.*, 2024). Bio-oil is associated with several drawbacks, including corrosiveness resulting from elevated organic acid levels, reduced calorific value due to heightened oxygen and water content, and instability arising from its intricate composition. These challenges pose difficulties in the upgrading process and hinder the direct application of bio-oil as a fuel in internal combustion engines (Zhang *et al.*, 2024).

Syngas

H₂ is the most abundant element in the universe, yet it primarily exists in chemical conjunction with other elements, such as carbon and oxygen, resulting in compounds like H₂O, fossil fuels, biomass, and an assortment of hydrocarbons. To harness H₂ in its elemental form, a variety of methods have been developed, encompassing

thermochemical, electrochemical, photobiological, and photochemical processes (Tahir *et al.*, 2024). After the completion of the pyrolysis phase, the resulting carbon monoxide (CO) and hydrogen (H₂) gases are directed into the Fischer–Tropsch (F-T) process. In this subsequent stage, facilitated by a well-suited catalyst, the CO and H₂ gases undergo a chemical transformation, combining to form elongated hydrocarbon chains. This process involves the synthesis of extensive hydrocarbon compounds through the molecular bonding of the provided gases (Al-Qahtani, 2023).

Biochar

Char, obtained from non-biogenic feedstocks, or biochar, derived from biogenic feedstocks, typically exhibits elevated carbon content (>65%), a highly porous structure, and substantial quantities of extractable humic and fulvic acids, along with various nutrients like calcium, potassium, and phosphorus. Additionally, it boasts a high cation exchange capacity. Specific biochars have the capacity to serve as a nutrient source for the soil, offering a gradual release of nutrients to plants, thereby enhancing their growth. The quality and stability of biochar vary depending on specific parameters, which are contingent on the intended application (Volpi *et al.*, 2024). Biochar derived from sewage sludge is a beneficial soil amendment in agriculture, improving soil characteristics by augmenting nutrient levels, cation exchange capacity, water retention, and oxygen transmission. Despite these advantages, its application is hindered due to the existence of micropollutants like polycyclic aromatic hydrocarbons (PAHs), polychlorinated dibenzodioxins (PCDDs), polychlorinated dibenzofurans (PCDFs), polychlorinated biphenyls (PCBs), and volatile organic compounds (VOCs) (Schleederer *et al.*, 2024).

Materials and Methods

Preparation of Locust Beans Pod

Locust bean pods sourced from Abubakar Tafawa Balewa University Bauchi's farm will undergo preliminary processing stages. Locust beans pods were collected and stored in polyethylene bags before being transport to the laboratory. The biomass was washed with distilled water and dried under 100°C for a day using oven drier (ASTM E1756-08). The dried locust beans pods were crushed using mortar and pestle and further grounded using a blender sieving to attain the desired particle size of 0.2mm (Mohammed *et al.*, 2017).

Fourier Infrared Spectroscopy (FTIR) of Locust Beans Pods

The biomass sample was finely ground to a particle size of less than 100 micrometers to ensure uniformity. It was then dried at 105 °C to eliminate any residual moisture that could interfere with analysis. A small quantity of the dried sample, typically between 1 and 2 milligram was placed directly on the ATR crystal surface. Consistent pressure was then applied using the anvil to ensure proper contact between the sample and the crystal for accurate spectral acquisition (Amponsem *et al.*, 2022).

Proximate Analysis of Locust Beans Pods

Proximate analysis assesses four main components of biomass: moisture content, volatile matter, ash content, and fixed carbon (determined by subtraction).

Moisture content was determined by measuring the weight of a pre-dried, empty crucible (W_1). Then, introduce a specific amount of biomass into the crucible and note the new total weight (W_2). Place the crucible in an oven set to 105 °C and heat the sample until its weight no longer changes, indicating complete moisture removal. Once heating is complete, allow the crucible to cool in a desiccator to avoid moisture uptake from the environment, and then record the final weight (W_3) (ASTM E871). The volatile matter of the sample was obtained by using the oven-dried biomass sample obtained from the moisture content test, transfer it into a covered crucible and place it in a muffle furnace. Heat the sample at 950 °C for a duration of 7 minutes to allow for volatile matter release. After heating, allow the crucible to cool in a desiccator to prevent moisture absorption, then record the resulting weight (W_4) (ASTM E872). The ash content of the biomass was determined by placing the sample in an uncovered crucible and subjected to heating at 600 °C for 4 hours in a muffle furnace to ensure full combustion of the organic content. Once the heating process is complete, the crucible is cooled in a desiccator to avoid moisture absorption, and the weight of the remaining ash (W_5) is then recorded (ASTM E1755). Fixed carbon content for dry basis is determined by formula (by difference):

$$\text{Fixed Carbon (\%)} = 100 - (\text{Volatile} + \text{Ash})$$

Thermogravimetric Analysis of Locust Beans Pods

The thermogravimetric analysis instrument was calibrated for both mass and temperature following the manufacturer's instructions. Once calibration was complete, a purge gas commonly nitrogen was set at a flow rate typically ranging from 20 to 100 mL/min. A clean, empty crucible was first weighed, after which a known quantity of biomass was added, and the total weight is recorded. The thermal analysis was then performed by heating the sample from room temperature (around 25 °C) up to 900 °C at a constant heating rate of 10 °C per minute, under an inert atmosphere such as nitrogen, to simulate a pyrolysis environment (ASTM E2550).

Differential Thermal Analysis of Locust Beans Pods

The instrument was calibrated for both temperature and heat flow according to the manufacturer's guidelines. Appropriate crucibles are then selected and placed inside the DTA furnace. A purge gas, typically nitrogen for pyrolysis applications was set along with the required flow rate. The biomass sample was loaded into one crucible, while a reference material, such as alumina was placed in the other. Both crucibles were then positioned within the furnace chamber. The analysis was carried out by heating the samples from ambient temperature (approximately 25 °C) up to 900 °C at a controlled heating rate of 10 °C per minute under a nitrogen atmosphere (ASTM E472).

Results and Discussion
FTIR Characterization of Locust Bean Pod

Fourier Transform Infrared (FTIR) spectroscopy was employed to identify the functional groups present in the locust bean pod biomass, which are critical in determining its pyrolysis behavior. The FTIR spectrum of the locust bean pod as shown in Figure 1, and reveals various absorption peaks corresponding to vibrational modes of chemical bonds in the biomass. The following key peaks were observed in the FTIR spectrum of the locust bean pod as shown in Table 1;

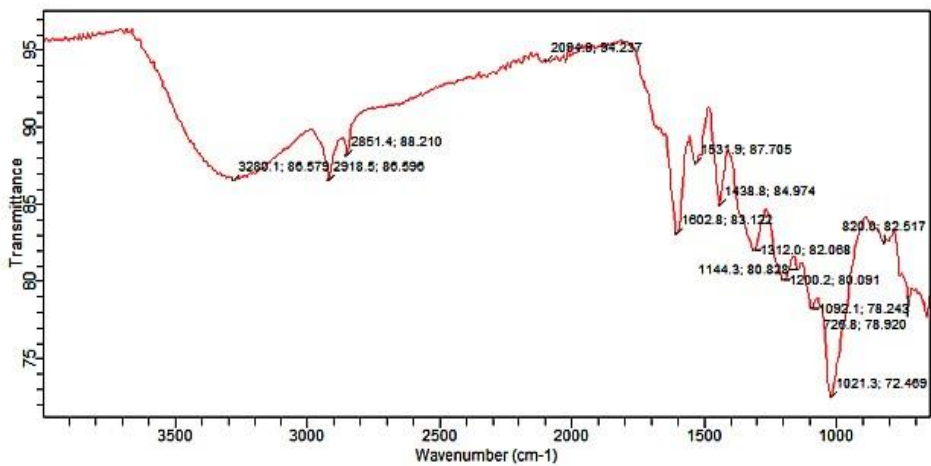


Figure 1: FTIR Spectra of locust beans pod

Table 1: FTIR Vibrational Frequencies of Locust beans pod

Wavenumber (cm ⁻¹)	Assigned Functional Group	Associated Biomass Component
3298	O–H stretching (broad)	Cellulose, hemicellulose (moisture, hydroxyl groups)
2915, 2851	C–H stretching (aliphatic)	Cellulose, hemicellulose (–CH ₂ – groups)
1735	C=O and C=C stretching	Hemicellulose (acetyl esters), lignin (aromatic structures)
1515	Aromatic C=C stretching	Lignin aromatic ring structures
1240	C–O stretching and C–O–C	Ether linkages in cellulose and hemicellulose
875, 785	C–H bending (aromatics, phenols)	Lignin and trace phenolic compounds

The FTIR spectrum of locust bean pod biomass shows characteristic lignocellulosic absorption bands corresponding to cellulose, hemicellulose, and lignin components. The broad absorption band observed near 3298 cm⁻¹ corresponds to O–H stretching vibrations associated with hydroxyl groups present in cellulose and hemicellulose. Similar bands have been reported in FTIR analyses of rice husk and other agricultural residues, confirming the

hydrophilic and oxygenated nature of lignocellulosic biomass. The peaks observed at 2915 and 2851 cm^{-1} in locust bean pod correspond to aliphatic C–H stretching vibrations associated with carbohydrate structures in cellulose and hemicellulose. These functional groups are commonly detected in rice husk FTIR spectra and indicate the presence of volatile organic structures that contribute to bio-oil formation during pyrolysis (Kachroo et al., 2024).

The carbonyl absorption band around 1735 cm^{-1} , attributed to C=O stretching vibrations of acetyl and ester groups in hemicellulose, is also consistent with observations in rice husk biomass characterization studies. Hemicellulose decomposition typically occurs at lower temperatures during pyrolysis, producing oxygenated compounds such as acids, aldehydes, and ketones. The absorption band at approximately 1515 cm^{-1} corresponds to aromatic C=C stretching vibrations associated with lignin structures. Lignin is known to contribute to char formation and phenolic compounds during biomass pyrolysis. Studies on lignocellulosic biomass pyrolysis consistently report lignin-derived aromatic structures as major contributors to thermal stability and biochar formation. The band observed near 1240 cm^{-1} , assigned to C–O–C stretching vibrations, indicates ether linkages in cellulose and hemicellulose. Similar functional groups have been identified in FTIR characterization of rice husk and other biomass materials, confirming their lignocellulosic composition. In addition, aromatic C–H bending vibrations observed between 875 and 785 cm^{-1} confirm the presence of lignin-derived phenolic structures, which are important precursors for phenolic compounds in pyrolysis oil (Manyatse et al., 2025).

Despite these similarities, rice husk contains significant inorganic mineral content, particularly silica, which influences its thermochemical behavior. Studies have shown that rice husk contains high SiO_2 content, which increases ash formation during pyrolysis and may reduce bio-oil yield (Tsai et al., 2023). Overall, the FTIR results confirm that locust bean pod possesses the typical lignocellulosic functional groups required for thermochemical conversion. Compared with rice husk, the lower mineral content of locust bean pod suggests improved suitability for pyrolysis, with potentially higher volatile release and reduced ash formation. Lignocellulosic biomass containing cellulose, hemicellulose, and lignin has been widely reported as an ideal feedstock for pyrolysis-based bio-oil and biochar production.

Proximate Analysis Locust Beans Pods

The proximate analysis of locust bean pod as shown in Table 2, with a moisture content of 5.5%, ash content of 13%, volatile matter of 76%, and fixed carbon of 11%, as depicted in Table 2, indicates its strong potential as a thermochemical conversion feedstock, particularly for bio-oil production. The low moisture content aligns with acceptable ranges for pyrolysis (<10%), minimizing energy losses during drying and enhancing thermal conversion efficiency (Al-Rumaihi et al., 2022). The volatile matter, which represents the portion of the biomass that vaporizes during heating, is considerably high (76%), suggesting

a high yield of condensable volatiles and permanent gases which are key indicators of suitability for bio-oil and syngas production. The FTIR spectrum presented is representative of repeated scans conducted under identical operating conditions. Peak positions were found to be consistent across measurements, indicating good spectral reproducibility.

Table 2: Proximate analysis of Locust beans pod

Analysis	wt (%)
Moisture Content	5.5
Volatile matter content	76
Ash content	13
Fixed carbon	11

In comparison, recent studies on rice husk report moisture contents ranging from 5.87% in briquetted forms to 10.6% in raw husk, ash contents between 5.3% and 12.1%, volatile matter values around 58.8%, and fixed carbon ranging from 15.8% to as high as 74% depending on processing (Akinyemi et al., 2022). While rice husk shows a more balanced composition with moderate ash and higher fixed carbon, which favors char production, the locust beans pod's higher volatile content implies a greater propensity for liquid fuel generation under fast pyrolysis conditions. However, the relatively high ash content of locust beans pod (13%) compared to the lower values observed in rice husk briquettes (5.3%) could present operational challenges, such as reactor fouling or reduced heating value, requiring mitigation through pre-treatment or blending with low-ash biomass. The fixed carbon content of 11% is lower than that of rice husk, indicating reduced char yield, which may be favorable if the primary aim is to maximize liquid product output rather than solid fuel. A limitation of the present study is that the physicochemical characterization results were obtained from single analytical determinations, and replicate measurements were not performed. Consequently, statistical parameters such as mean values and standard deviations could not be reported. Future studies should include replicate analyses to assess experimental variability and improve the statistical reliability of the characterization data.

Thermogravimetric and Differential Thermal Analysis of Locust Beans Pods

Thermogravimetric Analysis (TGA) and Differential thermal Analysis (DTA) are essential techniques used to evaluate the thermal stability and decomposition profile of biomass. These methods provide critical insight into how biomass materials respond to increasing temperatures under inert conditions, which is especially relevant for pyrolysis applications.

Thermogravimetric Analysis (TGA)

The TGA curve (red solid line) depicted by Figure 2, shows the progressive mass loss (%) of the sample as a function of temperature (°C). From the curve, three distinct regions of weight loss can be observed:

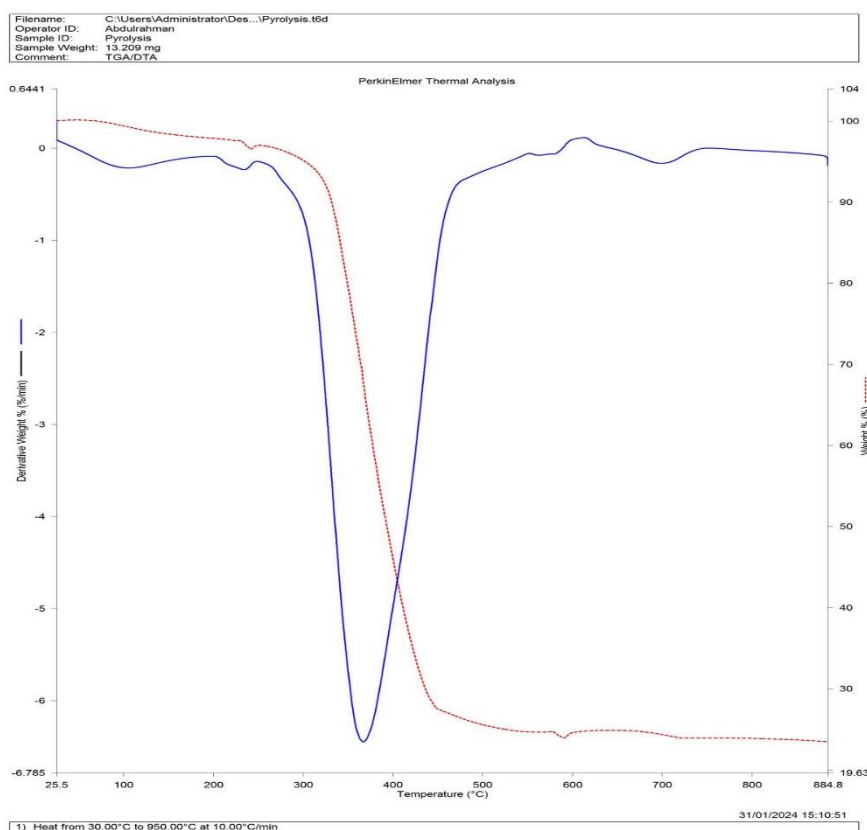


Figure 2: Thermogravimetric Analysis/ Differential Thermal Analysis of Locust Beans pod

- Initial Region (Below ~150 °C): A minor mass loss is observed in this temperature range, typically attributed to the evaporation of moisture and physically bound water. This is consistent with the low moisture content of the locust bean pod as observed in proximate analysis (5.5%).
- Primary Decomposition Region (~200 °C to 400 °C): A significant and sharp drop in weight occurs within this range, indicating the thermal degradation of volatile components such as hemicellulose and cellulose. This region accounts for the bulk of biomass decomposition and corresponds to the release of condensable volatiles essential for bio-oil formation. The onset of this rapid degradation begins around 290–310 °C, with peak decomposition occurring around 350–380 °C.
- Final Region (Above 400 °C): Beyond 400 °C, the TGA curve flattens, showing minimal mass loss. This phase indicates the decomposition of lignin and the formation of fixed carbon (char). The residual mass at approximately 800–850 °C is

around 19.83%, which corresponds to the ash content and residual char that did not volatilize.

This thermal behavior suggests that the major decomposition zone for the locust bean pod is concentrated below 500 °C, reinforcing its suitability for fast pyrolysis processes that operate within this temperature range (Lin et al., 2021).

Differential thermal Analysis (DTA)

The DTA curve (blue solid line) in Figure 2, represents the rate of weight loss (%/min) with respect to temperature and provides more detailed insight into the decomposition dynamics:

- A distinct peak is observed between 350–380 °C, which signifies the maximum rate of weight loss during pyrolysis. This peak corresponds to the most intense phase of thermal decomposition, dominated by the breakdown of cellulose and hemicellulose.
- The sharpness and magnitude of the DTA peak indicate that the biomass undergoes rapid thermal degradation, which is characteristic of volatile-rich biomass. This behavior aligns well with the ultimate analysis, which showed relatively high hydrogen and moderate carbon levels, both of which support intense devolatilization.
- The absence of multiple sharp peaks implies that the decomposition occurred in well-defined stages, with a primary degradation event rather than a broad, staggered thermal breakdown.

The thermal degradation behavior exhibited in both TGA and DTA curves suggests that the locust bean pod is highly reactive in the 300–450 °C range, making it ideal for fast pyrolysis applications aimed at maximizing bio-oil yield. The presence of a single dominant decomposition peak simplifies reactor design and control. The final residue (~20%) confirms a moderate char and ash yield, which complements findings from proximate and ultimate analyses. Overall, the TGA/DTA results confirm that locust bean pod is thermally suitable for pyrolysis, especially when targeting liquid products under controlled heating rates and inert conditions (Lin et al., 2021).

Conclusions

The FTIR analysis confirmed the lignocellulosic nature of the locust bean pod biomass through the presence of hydroxyl, aliphatic C–H, carbonyl, aromatic C=C, and ether functional groups associated with cellulose, hemicellulose, and lignin. These oxygenated and aromatic structures indicate strong potential for the production of bio-oil, syngas, and biochar during pyrolysis.

The proximate analyses demonstrated that locust bean pod possesses favourable characteristics for thermochemical conversion, with low moisture content (5.5 wt%), high

volatile matter content (76 wt%), fixed carbon content (11 wt%) The high volatile matter content supports enhanced bio-oil production.

The combined TGA and DTA analyses revealed a typical three-stage thermal degradation pattern consisting of moisture removal, active devolatilization of hemicellulose and cellulose, and subsequent lignin decomposition and char formation. The maximum decomposition rate occurred within the temperature range of 350–380°C, while the major degradation zone was concentrated between 300 and 450°C, confirming the suitability of locust bean pod for pyrolysis operations within this temperature window.

Overall, the physicochemical and thermal characterization results establish locust bean pod as a promising and sustainable lignocellulosic feedstock for pyrolysis. Its favourable chemical composition, high volatile content, and desirable thermal degradation behaviour support its potential for bio-oil production and agricultural waste valorization, contributing to renewable energy development and environmental sustainability.

Recommendations

1. Experimental pyrolysis investigations should be conducted to quantify bio-oil, biochar, and syngas yields at different operating temperatures and heating rates.
2. Further studies should focus on optimizing parameters such as temperature, residence time, particle size, and heating rate to maximize bio-oil production and quality.
3. Detailed characterization of bio-oil, biochar, and gaseous products using techniques such as GC-MS, SEM, BET, and elemental analysis is recommended.

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