KWARA STATE POLYTECHNIC

FABRICATION AND PERFORMANCE EVALUATION OF WASTE WOOD PYROLYSIS MACHINE

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HND/22/MEC/FT/0072

A PROJECT REPORT SUBMITTED TO DEPARTMENT OF MECHANICAL ENGINEERING, INSTITUTE OF TECHNOLOGY, KWARA STATE POLYTECHNIC, ILORIN

IN PARTIAL FULFILLMENT FOR THE REQUIREMENT OF THE AWARD OF HIGH NATIONAL DIPLOMA (MECHANICAL ENGINEERING) MANUFACTURING & POWER AND PLANT OPTION

ILORIN, NIGERIA

JULY 2025

CERTIFICATION

this is to certify that this report title **FABRICATION AND PERFORMANCE EVALUATION OF WASTE WOOD PYROLYSIS MACHINE** was prepared by **OLANREWAJU KUDUS TAIWO** with matric number **HND/22/MEC/FT/0072** meet the requirements for the award of higher national diploma in the department of mechanical engineering kwara State Polytechnic and was approved for the contribution to knowledge and literacy presentation

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DEDICATION

I dedicate this project to Almighty Allah the creator, the cherisher, and the sustainer of mankind for His grace, protection, and love upon me as a privilege to start and complete my Higher National Diploma (HND) program and project successfully. And also, to my beloved parents *Mr. & Mrs. OLANREWAJU.*

ACKNOWLEDGEMENT

My sincere appreciation goes to my parents, my siblings, my entire households, and my friends and course mates who in one or two ways contribute towards the success of my Higher National Diploma (HND) program and project. May Allah replenish and crown you all your endeavors. I pray, Allah forgive my mother her shortcomings, accept her return, and grant her the best place in Aljannah. Amen. My dear hearted profound gratitude goes to my amiable supervisor, H.O.D Mechanical Engineering ENGR. AYANTOLA A.A who made himself available for proper guidance and to make necessary correction of this project. Big thanks to you sir.

ABSTRACT

This project focuses on the **Fabrication and Performance Evaluation of a Waste Wood Pyrolysis Machine** designed to convert wood-based biomass into valuable byproducts—**biochar**, **bio-oil**, and **syngas**—through the process of thermal decomposition in an oxygen-limited environment. With increasing concerns over environmental sustainability and energy diversification, pyrolysis presents a promising method for converting wood waste into renewable energy sources and carbon-rich materials. The system developed in this study comprises a reactor chamber, heating unit, condenser, gas outlet, and char collection unit, all engineered for efficient and controlled pyrolysis.

The machine was fabricated using locally sourced materials with considerations for cost-effectiveness, thermal efficiency, and operational safety. During testing, dried waste wood was pyrolyzed at temperatures ranging from 400°C to 550°C. The output was analyzed to determine the **yield and quality** of the resulting products. **Biochar** exhibited a fixed carbon content of over 60%, making it suitable for soil amendment and filtration applications. **Bio-oil** showed a calorific value of approximately 17.5 MJ/kg, suggesting its viability for blending with conventional fuels or chemical feedstock. The **syngas** generated, with an energy content of 4.5–6 MJ/m^3, demonstrated potential for onsite heating or energy recovery.

The results validate the functionality of the machine and demonstrate its potential in **Waste Management**, **Renewable Energy Production**, and **Environmental Conservation**. This project thus contributes to sustainable development goals by offering a practical solution for valorizing wood waste through pyrolysis technology.

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CHAPTER ONE

1.0 INTRODUCTION

1.1 PREAMBLE (BASIC IMPORTATION)

Pyrolysis is a thermochemical decomposition process that converts organic materials into useful by-products through thermal degradation in the absence of oxygen. It is a versatile method particularly suited for transforming biomass materials such as waste wood, agricultural residues, and municipal solid waste into valuable resources including biochar, bio-oil, and syngas. In an era marked by environmental concerns and resource scarcity, pyrolysis has emerged as a sustainable solution with applications in renewable energy, waste management, agriculture, and materials science (Bridgwater, 2012).

Globally, millions of tons of wood waste are generated annually through deforestation, timber production, and construction activities. According to the World Bank (2020), over 2 billion tons of municipal solid waste is produced each year, with up to 30% consisting of biomass materials such as wood, paper, and organic matter. In developing nations like Nigeria, wood waste from sawmills, carpentry workshops, and domestic firewood use is often discarded, burnt openly, or left to decay, causing significant environmental and health hazards (UNEP, 2021).

Pyrolysis serves as a cleaner, more efficient alternative to incineration or landfill disposal, enabling the recovery of energy and materials while minimizing harmful emissions. Through the pyrolysis process, waste wood can be transformed into stable carbon-rich biochar, a liquid bio-oil with combustible properties, and a syngas suitable for local energy generation. This aligns closely with the United Nations Sustainable Development Goals (SDGs), particularly Goal 7 (Affordable and Clean Energy), Goal 12 (Responsible Consumption and Production), and Goal 13 (Climate Action).

The development and deployment of a localized, cost-effective pyrolysis machine is essential for community-level applications. It offers a viable pathway to address rural energy deficits, create employment, and promote sustainable practices. Locally fabricated pyrolysis systems are especially relevant in sub-Saharan Africa, where imported technologies may be unaffordable or ill-suited to local contexts (Ogunniyi et al., 2018).

This project aims to design, fabricate, and evaluate the performance of a waste wood pyrolysis machine suitable for use in rural and semi-urban communities. By harnessing locally available materials and engineering expertise, the project demonstrates the feasibility of producing a functional and efficient pyrolysis unit that can contribute to sustainable waste-to-energy solutions.

1.2 HISTORY OF WOOD PYROLYSIS

The historical use of pyrolysis can be traced back over 5000 years. In ancient civilizations such as Egypt, Greece, and China, wood was heated in low-oxygen environments to produce charcoal, which served as a primary fuel for cooking, metallurgy, and ceremonial practices. Early kilns were rudimentary, consisting of earth pits or clay enclosures where wood was stacked and covered to smolder slowly over several days.

The scientific exploration of pyrolysis began in the 17th and 18th centuries with the work of chemists like Robert Boyle and Antoine Lavoisier, who studied the thermal decomposition of organic matter. By the 19th century, pyrolysis had become an industrial process used to extract chemicals like wood tar, acetic acid, and methanol from hardwoods (Brownsort, 2009). These chemicals were essential for producing dyes, solvents, and explosives.

During the Industrial Revolution, pyrolysis was closely associated with the manufacture of illuminating gas and coke for steel production. Coal pyrolysis formed the backbone of urban gas lighting systems in cities across Europe and North America. However, with the advent of electricity and petroleum-based fuels, pyrolysis saw a decline in widespread use by the mid-20th century.

The energy crises of the 1970s revived global interest in pyrolysis as an alternative to fossil fuels. Researchers began to explore biomass pyrolysis for renewable energy applications, leading to the development of more sophisticated reactors and process control systems. In the 21st century, the rise of biochar as a tool for carbon sequestration, soil improvement, and climate mitigation has further spurred interest in pyrolysis technology (Lehmann & Joseph, 2015).

In Nigeria and other parts of Africa, traditional charcoal-making methods based on slow pyrolysis remain prevalent in rural communities. These methods, while accessible, are inefficient and environmentally damaging due to uncontrolled emissions and low yields. The challenge and opportunity lie in upgrading such practices through improved reactor designs that combine traditional knowledge with modern engineering.

1.3 TYPES OF WOOD FOR PYROLYSIS

The nature and characteristics of wood used in pyrolysis significantly influence the efficiency of the process and the quality of the resulting products. Waste wood, as a feedstock, varies widely in terms of density, moisture content, chemical composition, and size. The classification of wood suitable for pyrolysis generally falls under four categories:

1.3.1 HARDWOOD

Examples include oak, iroko, mahogany, and beech. These woods are dense and contain a higher proportion of lignin, which favors the formation of biochar. Due to their fibrous structure, hardwoods produce stable char and require higher energy input for complete thermal degradation.

FIG. 1.3.3 Diagram of Hardwood

1.3.2 SOFTWOOD

Includes species like pine, fir, and cedar. Softwoods have more resinous components and higher cellulose content, making them more volatile during pyrolysis. They are generally easier to process and yield more condensable vapors, translating into higher bio-oil yields.

FIG. 1.3.2 Diagram of Softwood

1.3.3 TREATED OR ENGINEERED WOOD PRODUCTS (EWPs)

Such as plywood, MDF, and particleboard. These contain adhesives, synthetic resins, and sometimes preservatives, which complicate pyrolysis due to the release of hazardous gases. These types require pretreatment or are excluded for environmental safety.

FIG. 1.3.3 Diagram of Treated or Engineered Wood Products (EWPS)

1.3.4 AGRICULTURAL WOODY RESIDUES

These include pruned branches, fruit tree trimmings, coconut shells, and palm fronds. Though less consistent in structure, these sources are abundant and provide a sustainable pyrolysis feedstock, especially in rural settings.

FIG. 1.3.4 Diagram of Agricultural Woody Residues

1.4 **METHOD OF PYROLYZING WOOD**

There are various methods of conducting pyrolysis on wood, and these methods are categorized based on factors such as temperature, heating rate, and vapor residence time. The selection of a suitable pyrolysis method is vital for determining the dominant type of product—biochar, bio-oil, or syngas. The three main types of pyrolysis methods include slow pyrolysis, fast pyrolysis, and flash pyrolysis, with microwave-assisted pyrolysis and hydrothermal carbonization as recent innovations. (Mohan, Pittman and Steele, 2006; Wang et al., 2017).

1.4.1 SLOW PYROLYSIS

This is conducted at relatively low temperatures (300–500°C) and at slow heating rates with long residence times, typically ranging from several minutes to hours. This method favors the production of biochar due to the extended thermal degradation of lignocellulosic material. Slow pyrolysis is particularly suitable for applications where the goal is to enhance soil quality or sequester carbon through biochar application

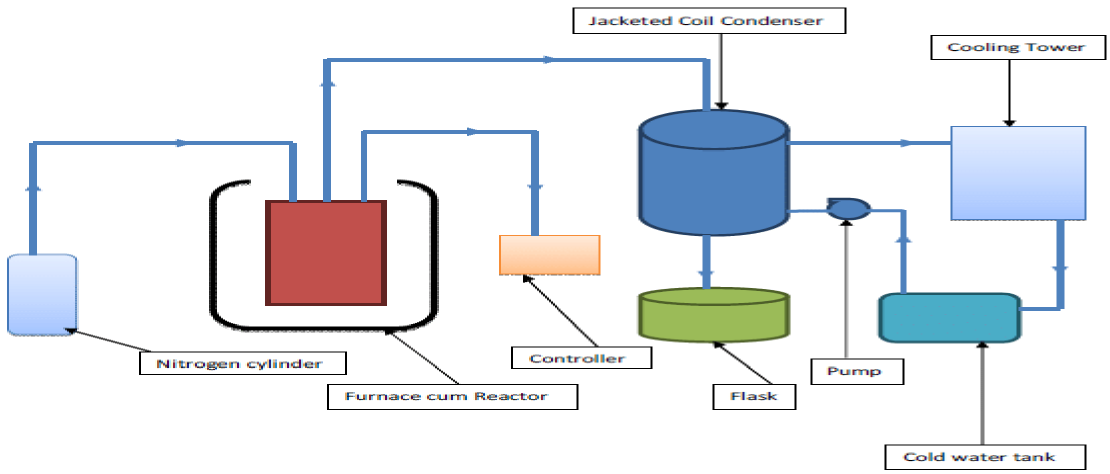

Fig. 1.4.1 Diagram of Slow Pyrolysis

1.4.2 FAST PYROLYSIS,

This contrast, is designed to maximize the yield of bio-oil. It operates at moderate temperatures (~500°C), but with rapid heating rates and very short vapor residence times—usually less than two seconds. Feedstock must be finely ground and pre-dried to ensure uniform heat transfer. This method is more complex and requires precise control of process parameters and a well-designed condensation system to quickly capture the condensable vapors before they degrade.

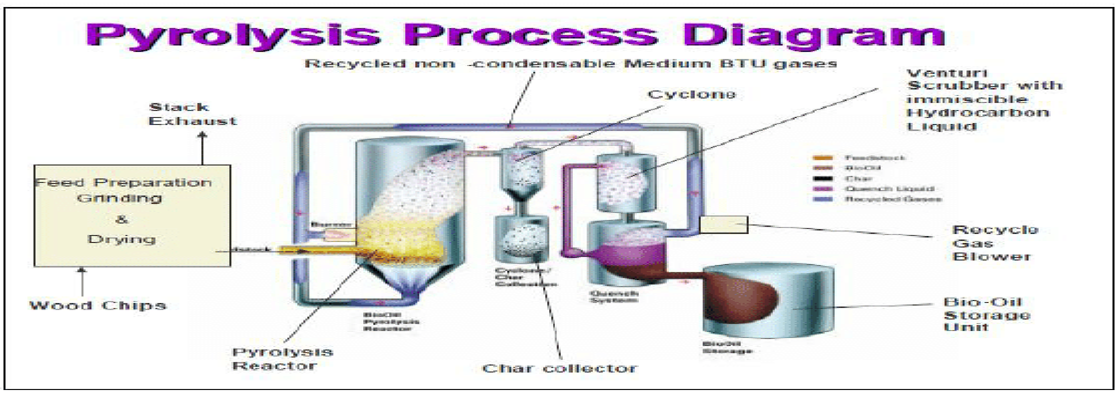

Fig 1.4.2 Diagram of Fast Pyrolysis

1.4.3 FLASH PYROLYSIS

This represents an extreme version of fast pyrolysis, with even faster heating rates and residence times measured in milliseconds. It is suitable for gas-phase reactions and typically yields large quantities of non-condensable gases such as hydrogen and carbon monoxide.

In recent years, microwave-assisted pyrolysis has gained traction due to its ability to offer rapid and volumetric heating using electromagnetic radiation. It shows promise for small-scale decentralized energy systems but remains relatively costly and less commercialized.

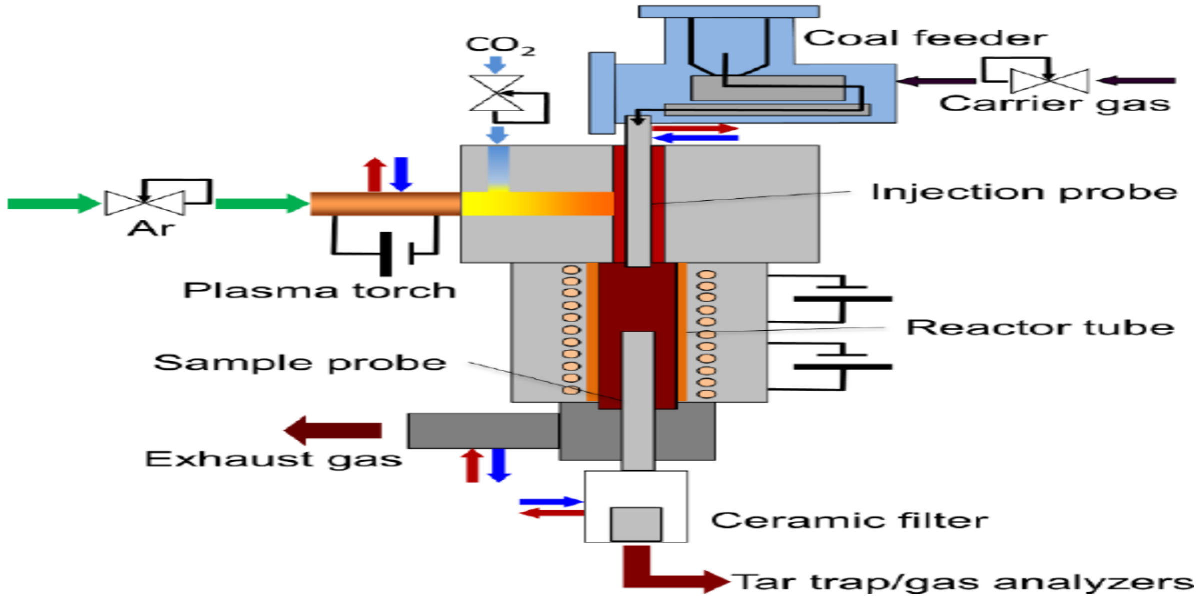

Fig 1.4.3 Diagram of Flash Pyrolysis

1.4.4 HYDROTHERMAL PYROLYSIS

This carbonization is another alternative method, especially useful for wet biomass. It involves heating biomass in water under pressure, producing a carbon-rich solid product without the need for extensive drying. This method, however, is not commonly used for wood due to its relatively low moisture content.

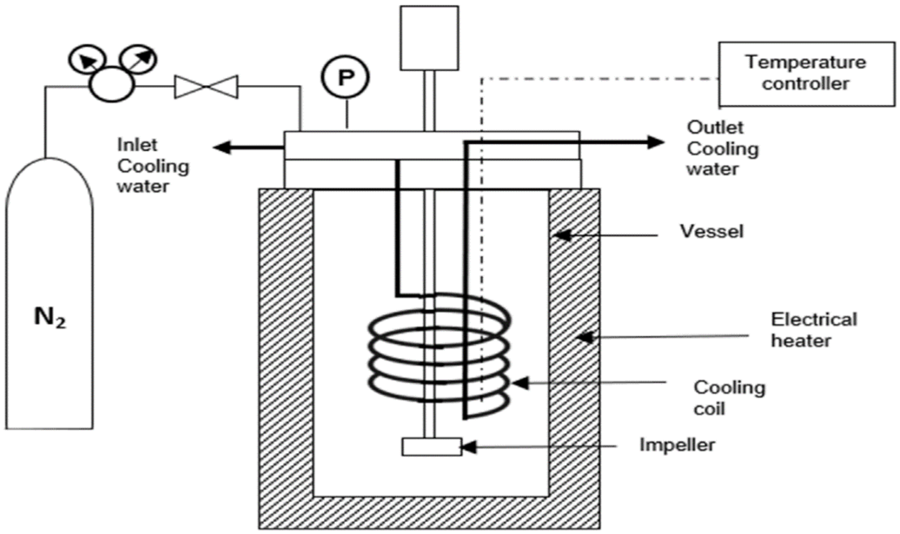

Fig 1.4.4 Diagram of hydrothermal pyrolysis

In practical terms, for rural or small-scale applications involving waste wood, slow pyrolysis remains the most cost-effective and technically feasible method. It requires simpler reactor design, lower energy input, and offers a balance between energy recovery and by-product utility. Each method presents distinct advantages and is selected based on specific operational goals and the desired distribution of products. (Libra et al., 2011).

TABLE 1.4: APPLICATION SUMMARY OF PYROLYSIS PRODUCTS

Product	Primary Uses	Secondary Uses
Biochar	Soil amendment, filtration, carbon sequestration	Construction filler, composting enhancer
Bio-oil	Fuel (direct/processed), industrial chemicals	Pesticides, preservatives
Syngas	Electricity, heat, internal combustion	Hydrogen production, synthetic fuels

1.5 TYPES OF WASTE WOOD PYROLYSIS MACHINES

Pyrolysis machines vary in design, scale, and mode of operation, but all are developed to serve the same core function: the controlled thermal decomposition of organic biomass without oxygen. Depending on technological sophistication, user needs, and economic constraints, waste wood pyrolysis machines may be classified into batch, semi-batch, and continuous systems.

Batch pyrolysis machines are typically simple in design and well-suited for small-scale or rural applications. These systems process wood in set amounts (batches), allowing for easier construction, lower cost, and minimal control requirements. However, they are limited by longer cycle times, lower throughput, and inefficiencies related to heating and cooling periods. They are best suited for communities or individuals seeking to produce biochar or bio-oil on a non-commercial scale.

Semi-batch pyrolysis units introduce partial automation, where feeding and product removal may be manual or partially mechanized. These systems offer a middle ground between batch and continuous setups, balancing cost and performance. They are more efficient than batch systems and offer greater consistency in product quality.

Continuous pyrolysis machines represent the most advanced and industrialized form. They feature automated feeding, continuous biomass conversion, and uninterrupted collection of bio-oil, syngas, and char. Continuous systems operate at higher temperatures, often employ screw or rotary reactors, and are supported by robust control systems for optimal operation. They are ideal for large-scale commercial ventures or centralized waste management authorities seeking to convert significant volumes of biomass into energy or chemicals.

Other classifications of pyrolysis machines include fixed-bed, fluidized-bed, rotary kiln, and auger-type reactors. Fixed-bed reactors are common in batch designs due to their simplicity and minimal maintenance needs. Fluidized-bed systems, which utilize a bed of inert particles agitated by gas flow, offer excellent heat transfer and scalability, particularly for fast pyrolysis. Rotary kilns and auger reactors are favored for continuous processes where feedstock size and uniformity can be controlled.

The design and choice of a pyrolysis machine depend heavily on the end-use of products, available feedstock, operational capacity, and local technological capacity. For developing regions, simpler models with locally available materials and manual operation are preferable due to their affordability and ease of maintenance.

As technological and material innovations continue to evolve, pyrolysis machines are increasingly incorporating modular designs, energy recovery systems, and emission control units, expanding their viability across diverse applications and economic contexts.

1.6 CHARACTERISTICS OF WASTE WOOD PYROLYSIS PRODUCTS

The products derived from pyrolyzing waste wood vary based on feedstock type and operating conditions. The three primary products are biochar, bio-oil, and syngas.

1. Biochar

A solid, carbon-rich residue that resembles charcoal. It is produced in high amounts during slow pyrolysis.

Characteristics:

- Carbon content: 60–90%
- Surface area: 100–300 m^2/g
- Ash content: 5–10%
- pH: typically alkaline (7.5–10)

Biochar has a porous structure, making it suitable for soil amendment, water filtration, and carbon sequestration. Its properties can vary significantly depending on feedstock and pyrolysis temperature.

2. Bio-oil

A dark brown, viscous liquid containing oxygenated organic compounds including acids, aldehydes, phenols, ketones, and water.

CHARACTERISTICS:

- Heating value: 16–23 MJ/kg
- Water content: 15–30%
- Density: ~1.1 g/cm³

Bio-oil has potential as a fuel or chemical feedstock but often requires upgrading due to its acidity, instability, and water content.

3. Syngas

A combustible gas mixture of carbon monoxide (CO), hydrogen (H_2), methane (CH_4), carbon dioxide (CO_2), and light hydrocarbons.

CHARACTERISTICS:

- Heating value: 5–20 MJ/m³ depending on composition
- Can be used directly in burners, gas turbines, or for electricity generation
- Helps maintain reactor temperature through internal combustion

Typical product yield distribution during slow pyrolysis of wood:

- Biochar: 30–35%
- Bio-oil: 25–35%
- Syngas: 30–40%

Graphical representation of yield (to be included in final layout) demonstrates how increasing temperature tends to favor syngas production while decreasing char yield.

1.7 APPLICATIONS OF WASTE WOOD PYROLYSIS PRODUCTS

Pyrolysis offers a broad range of applications, particularly in sustainable agriculture, energy recovery, and environmental management:

1. Biochar Applications

- Agriculture: Enhances soil fertility, water retention, and microbial activity. It improves crop yields and reduces fertilizer demand.
- Waste Management: Acts as a sorbent for heavy metals and organic pollutants.
- Carbon Sequestration: Stable for centuries, biochar can store atmospheric carbon in soils.
- Construction: Experimental use in cement and asphalt to enhance strength and reduce carbon footprint.

2. Bio-oil Applications

- Energy: Can be burned in modified boilers and stoves or upgraded to transportation fuels.
- Chemical Industry: Source of phenols, acetic acid, and other compounds for industrial use.
- Pesticides and Disinfectants: Due to its acidity and antimicrobial properties.

3. Syngas Applications

- Heat and Power Generation: Can be used to generate electricity in small-scale power plants.
- Heating: Employed in internal combustion engines or burners.
- Hydrogen Production: Source for hydrogen separation in fuel cell technologies.

1.8 TYPES OF PRODUCTION FROM WASTE WOOD PYROLYSIS

Depending on design intent and end-use, pyrolysis units can be optimized for different types of product output:

1. Solid Fuel Production (Biochar Briquettes)

- Biochar can be ground and pressed into briquettes using binders like starch or clay.
- Offers higher energy density, uniform size, and cleaner burning than traditional firewood.
- Widely used in clean cookstove initiatives across Africa and Asia.

2. Crude Bio-oil for Refinement

- Collected via condensation chambers
- Requires stabilization or catalytic upgrading to be used as a diesel or petrol substitute
- Research is ongoing on emulsification with diesel for hybrid fuel use

3. Syngas Recovery and Use

- Captured through gas exit ports and filtered
- Can power internal combustion engines, gas lamps, or heating systems
- Advanced systems integrate gas turbines for combined heat and power (CHP)

4. Biochar-Based Products

- Nutrient-enhanced biochar (e.g., biochar mixed with compost or NPK fertilizers)
- Activated carbon filters
- Biochar-infused bricks or construction materials

Each production type requires specific design considerations in the pyrolysis machine—such as insulation thickness, condenser design, feedstock handling, and residence time. For example, maximizing char yield requires longer residence time and lower peak temperatures, while maximizing oil production requires rapid heating and effective vapor condensation.

1.9 AIM AND OBJECTIVES

The aim of this project is to design, fabricate, and evaluate a functional waste wood pyrolysis machine capable of converting biomass waste into useful by-products such as biochar, bio-oil, and syngas for energy and environmental applications.

1.9.1 SPECIFIC OBJECTIVES:

- To study the thermochemical principles of pyrolysis and determine optimal conditions for efficient conversion.
- To select appropriate materials for constructing a small-scale pyrolysis unit using locally available resources.
- To design and fabricate the core components of a fixed-bed batch pyrolysis machine.
- To evaluate the performance of the pyrolysis machine based on yield, thermal efficiency, and operational safety.
- To analyze the properties of the pyrolysis products and assess their potential applications.
- To promote the use of pyrolysis as an eco-friendly alternative for managing wood waste in Nigeria and similar regions.

1.10 SCOPE OF THE PROJECT

a. This project encompasses the design, fabrication, and performance testing of a small-scale fixed-bed batch pyrolysis unit for converting waste wood into valuable by-products. The scope covers:
b. Theoretical background and literature review on pyrolysis processes and technologies.
c. Material selection based on cost, thermal stability, and mechanical properties.
d. Detailed mechanical design, including chamber size, insulation, gas outlets, and condensers.
e. Fabrication using standard workshop tools and locally sourced materials.
f. Experimental testing using common hardwood waste such as mahogany and iroko offcuts.
g. Analysis of biochar, bio-oil, and syngas yield and quality.
h. Recommendations for improved design, scalability, and environmental impact mitigation.

1.10.1 LIMITATIONS

a. No catalytic upgrading or advanced gas purification system is included.
b. The design is optimized for batch processing rather than continuous feed operation.
c. Limited by workshop equipment and availability of advanced instrumentation.

1.11 PROBLEM STATEMENT

In many parts of Nigeria and other developing countries, wood waste is generated in large quantities from sawmills, carpentry workshops, and domestic firewood use. This waste is often discarded, openly burned, or left to decay, contributing to environmental pollution, greenhouse gas emissions, and health hazards.

Simultaneously, communities face critical challenges related to energy access, particularly in off-grid rural areas. Traditional biomass use for cooking and heating is inefficient and harmful due to indoor air pollution.

Despite the potential of pyrolysis to transform biomass waste into clean energy and value-added products, the lack of affordable, locally fabricated pyrolysis systems limits adoption. Imported units are costly, technologically complex, and ill-suited to the local context.

This project seeks to address this gap by designing and constructing a cost-effective, easy-to-operate pyrolysis machine using local materials and expertise. It aims to provide a sustainable, scalable solution for managing wood waste while contributing to energy generation, environmental protection, and economic development.

CHAPTER TWO

2.1 LITERATURE REVIEW

The pyrolysis of biomass, particularly waste wood, has garnered significant academic and industrial attention due to its potential to transform underutilized biomass into valuable fuels and chemicals. Waste wood, an abundant by-product of forestry operations, sawmills, carpentry, and municipal waste, is often discarded or burned, leading to environmental degradation. In contrast, pyrolysis offers a controlled method of thermochemically decomposing this biomass in the absence of oxygen to produce three main products: biochar, bio-oil, and syngas. These products can be repurposed for soil enhancement, renewable energy generation, and industrial fuel substitution, respectively.

Biomass waste, including wood residues, has been identified as a critical resource for alternative energy systems. According to World Bank (2020), over 1.3 billion tonnes of wood waste are generated globally each year, with sub-Saharan Africa contributing a significant share. Nigeria alone produces millions of tonnes of wood waste annually, primarily from sawmills and furniture production (Aina, Ogundipe and Onuoha, 2019). Yet, despite the availability of this resource, its transformation into energy through pyrolysis remains underdeveloped in many parts of Africa.

The fundamentals of pyrolysis involve heating biomass to temperatures between 300°C and 700°C in the absence of oxygen. The decomposition reactions break down cellulose, hemicellulose, and lignin—the primary constituents of wood—into smaller molecules. The nature of the resulting products depends on several parameters, including heating rate, temperature, residence time, and feedstock characteristics. Slow pyrolysis, characterized by low heating rates and long residence times, favors the production of solid biochar. Fast pyrolysis, on the other hand, rapidly heats biomass, resulting in a higher yield of bio-oil (Bridgwater, 2012).

Temperature plays a decisive role in determining product distribution. Lower temperatures (around 350°C) favor solid yield, while higher temperatures (above 500°C) favor gaseous products. The moisture content and composition of the feedstock also influence the energy required and the efficiency of the process. For instance, hardwoods with higher lignin content tend to produce more stable and carbon-rich char (Demirbaş, 2004). Additionally, particle size affects the heat transfer rate; smaller particles tend to pyrolyze more uniformly.

Reactor design is equally crucial. Different pyrolysis reactors have been developed to cater to various operational needs. Fixed-bed reactors are commonly used in laboratory-scale and small-scale rural applications due to their simplicity and ease of construction. Rotary kilns and fluidized-bed reactors offer more consistent heating and mixing, making them suitable for larger operations. Auger reactors, which use a screw mechanism to move biomass through a heated chamber, allow continuous processing with precise control over residence time. Some innovative systems even explore microwave-assisted pyrolysis, where biomass is heated internally via electromagnetic waves, enhancing efficiency (Ronsse et al., 2013).

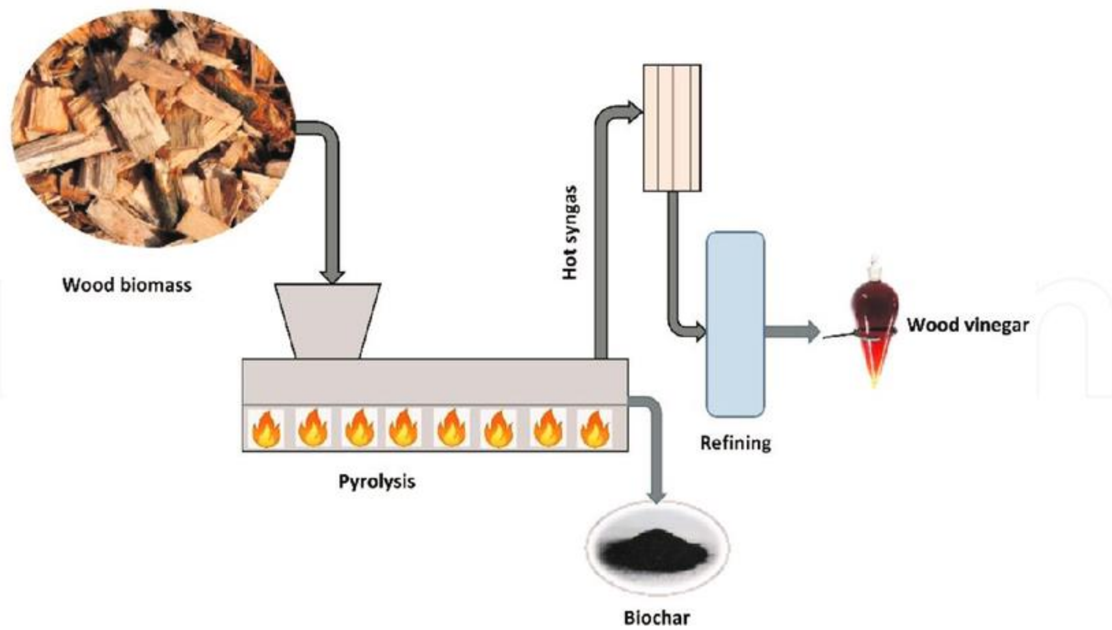

Fig. 2.1 Diagram of Wood Pyrolysis

Research in developing countries has focused on designing low-cost pyrolysis systems using readily available materials. Ogunniyi, Akinola and Bello (2018) successfully fabricated a fixed-bed batch pyrolysis unit using mild steel and refractory insulation, achieving an energy efficiency of 68% during test runs. Their approach highlights how resource-limited settings can still benefit from pyrolysis technologies by adapting simple yet effective designs. (Ogunniyi, Akinola and Bello (2018)

The end products of pyrolysis each hold significant economic and environmental value. Biochar, a porous black residue, has garnered attention for its use in agriculture. When applied to soil, it enhances water retention, nutrient availability, and microbial activity. Lehmann and Joseph (2015) emphasized that biochar also acts as a long-term carbon sink, thus contributing to climate change mitigation. Bio-oil, a viscous dark liquid, can be refined into transportation fuels or used directly in boilers and furnaces. Syngas, composed mainly of carbon monoxide, hydrogen, and methane, can power internal combustion engines or be used to sustain the pyrolysis process itself.

Various studies have further explored the performance of pyrolysis systems. Akinola, Ogunniyi and Alao (2020) investigated Nigerian hardwoods like mahogany and iroko, concluding that optimal pyrolysis occurred around 500°C, yielding stable char with over 65% fixed carbon content. Their findings underscore the importance of tailoring pyrolysis conditions to specific feedstock properties. Meanwhile, Bridgwater (2012) highlighted the scalability potential of fast pyrolysis, noting its compatibility with integrated bio-refinery systems. (Bridgwater (2012)

Despite the growing body of literature, notable gaps remain. Most existing studies are laboratory-based, with limited focus on field deployment and socio-economic integration. Few have addressed the long-term performance of locally fabricated units under real-world conditions. Moreover, awareness of the multifaceted benefits of biochar remains low in many rural communities. Consequently, the need for empirical studies that bridge engineering, environmental science, and rural development is critical.

Economically, the pyrolysis of waste wood offers promising revenue streams. The sale of biochar to farmers, bio-oil to industrial users, and syngas for energy generation can provide financial incentives for local entrepreneurs. Environmentally, it reduces open burning, which is a major contributor to air pollution and greenhouse gas emissions in developing countries. Socially, decentralized pyrolysis systems can create jobs, enhance energy access, and reduce dependence on firewood and kerosene, thereby improving public health and quality of life (World Bank, 2020).

In conclusion, the literature reveals a wealth of knowledge on the science and application of wood pyrolysis. However, there remains a pressing need for practical, community-based implementations in regions with abundant wood waste. The present study contributes to this field by fabricating a pyrolysis machine using local materials, evaluating its performance, and assessing its potential impact. In doing so, it bridges the gap between theory and application, providing a model for sustainable energy and waste management.

Recent studies such as Bridgwater (2012) and Tripathi et al. (2016) have demonstrated that pyrolysis, particularly fast pyrolysis, yields significant quantities of bio-oil with moderate energy content. These oils can be refined or directly used as fuel in boilers and engines, although their chemical complexity and high oxygen content necessitate further upgrading for commercial use. Conversely, slow pyrolysis remains more efficient for producing biochar—a highly porous carbon material beneficial for carbon sequestration, soil amendment, and pollutant adsorption (Lehmann & Joseph, 2015).

The chemical composition of pyrolysis products is greatly influenced by operating parameters such as heating rate, temperature, pressure, and feedstock type. According to Mohan et al. (2006), optimal biochar production is achieved at lower temperatures (~400°C), while bio-oil yield peaks between 450–550°C. Kinetic studies have established that the lignin, cellulose, and hemicellulose fractions of wood decompose at distinct temperature ranges, with cellulose contributing heavily to gas and oil phases, while lignin enhances char formation.

A comparative review underscores the suitability of different reactor designs for specific pyrolysis goals. Fixed-bed reactors are cost-effective and ideal for small-scale operations, whereas fluidized-bed and rotary kiln reactors support better temperature uniformity and higher throughput—making them more appropriate for industrial-scale applications. Auger and screw reactors have gained attention for their modularity and flexibility in integrating with decentralized biomass conversion systems.(Dhyani and Bhaskar (2018)

From a socio-economic standpoint, wood pyrolysis offers multiple benefits beyond energy production. It aids in reducing the environmental impact of wood waste disposal, promotes rural electrification, and supports local industries through bio-based products. Notable applications include its integration into agroforestry systems for biochar production and in circular urban economies where waste-to-energy initiatives are increasingly relevant (Woolf et al., 2010).

Environmental impact assessments (EIAs) of pyrolysis units have confirmed their lower carbon footprint compared to incineration and landfilling. Life Cycle Assessment (LCA) models, such as those discussed by Sadhukhan et al. (2014), reveal that biochar production can result in net negative emissions, primarily due to carbon retention and reduced need for chemical fertilizers.

Despite the advantages, several limitations exist. Challenges related to tar formation, inconsistent feedstock properties, and capital investment for continuous systems remain hurdles for widespread adoption, particularly in developing economies. Nonetheless, ongoing innovations in catalytic pyrolysis, co-pyrolysis with plastics or agricultural residues, and reactor automation continue to enhance the economic and operational viability of pyrolysis technology.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 MATERIALS

The fabrication of the waste wood pyrolysis machine requires the selection and application of suitable engineering materials that can withstand high temperatures, mechanical stress, and corrosive by-products. The materials must be locally available, cost-effective, and maintainable.

3.1.1 MATERIAL SELECTION CRITERIA

The materials selected for the fabrication of the waste wood pyrolysis machine were critically evaluated based on thermal, mechanical, environmental, and economic parameters. The operational environment of the pyrolysis system—characterized by high temperatures, corrosive vapors, and structural stress—demands materials with specific performance characteristics. Specifically, materials had to exhibit:

- Thermal stability to withstand temperatures between 400°C and 700°C, which are typical for pyrolysis.
- Corrosion resistance, particularly in sections exposed to acidic vapors and volatile organic compounds from biomass decomposition.
- Mechanical strength to support the weight of the feedstock and the vessel, resist internal pressure buildup, and endure transport-induced vibration.
- Economic feasibility, meaning locally available and affordable, especially in a resource-constrained rural setting.
- Fabrication compatibility, which includes machinability, weldability, and ease of forming or joining.
- Durability, to ensure long-term operation under thermal cycling and potential outdoor exposure.

These criteria guided the selection of mild steel, stainless steel, refractory brick, copper tubing, and angle iron for different parts of the pyrolysis machine.

3.1.2 PROPERTIES OF MATERIALS

The materials selected possess a variety of chemical and mechanical properties suitable for high-temperature, semi-industrial applications. These properties include thermal conductivity, tensile strength, thermal expansion coefficient, and corrosion resistance.

Mild Steel: Often preferred for pressure vessels and reactor chambers due to its weldability and affordability. It has a tensile strength of about 400–550 MPa and a melting point of 1425–1540°C. Though not highly corrosion-resistant, it performs well when thermally insulated and painted (Ogunniyi et al., 2018).

Stainless Steel (Grade 304): Offers enhanced resistance to corrosion caused by acetic acid, formaldehyde, and other pyrolysis-derived compounds. It has a melting point of 1400°C, yield strength of 205 MPa, and retains mechanical integrity at elevated temperatures (Demirbaş, 2004).

Refractory Brick (Alumina-Silica Composition): Used for lining the combustion chamber. They possess high compressive strength (>25 MPa), thermal stability up to 1400°C, and low thermal conductivity (Lehmann and Joseph, 2015). These bricks reduce fuel consumption by retaining heat.

Copper Tubes: Known for their excellent thermal conductivity (~400 W/m·K), copper is used in the condenser to rapidly dissipate heat and condense pyrolysis vapors into liquid. It also resists fouling and can be bent into coils easily (Bridgwater, 2012).

Angle Iron (Mild Steel Grade): Used for the frame and structural support due to its lightweight and rigidity. It has high load-bearing capacity and is easily sourced and welded.

3.1.3 CHOICE OF PROPER MATERIAL

The selection of the proper materials was directly influenced by the specific function of each machine component. For instance, the pyrolysis reactor had to handle high internal heat and pressure. Mild steel, combined with an insulating layer, was a cost-effective and technically viable solution. Stainless steel was necessary for the vapor outlet and piping, where corrosion resistance is crucial.

Refractory bricks were chosen for the combustion zone because they significantly improve fuel efficiency by reducing heat loss and retaining combustion heat. They are chemically inert and thermally shock-resistant, making them more durable than metallic alternatives.

For the condenser, copper tubing was used due to its high heat transfer efficiency, which is critical in condensing volatile gases into bio-oil. The support structure used angle iron, which offers mechanical stability and is available in various dimensions, ideal for custom fabrication.

Material testing and consultation with local fabricators ensured that the materials met project requirements and were adaptable to workshop-level fabrication methods.

The final selection was guided by the expected operational environment of the pyrolysis machine. Stainless steel (304) was selected for the main reactor chamber as it can withstand high thermal stress and resist acidic vapors. Mild steel was used for structural parts where heat exposure is minimal. All bolts, nuts, and fittings were galvanized to minimize rusting.

3.2. DESCRIPTION OF COMPONENT PARTS

The waste wood pyrolysis machine was assembled from various subunits, each serving a critical function in the thermal decomposition process:

3.2.1 REACTOR CHAMBER

A sealed cylindrical vessel with an internal diameter of 40 cm and a height of 50 cm, made from mild steel and lined with ceramic fiber insulation. It has a hinged lid secured with bolts and a gasket to maintain an airtight environment.

3.2.2 COMBUSTION CHAMBER

Located beneath the reactor, this compartment houses the primary heat source—typically biomass or charcoal. It is lined with refractory bricks for insulation and includes adjustable air inlets to regulate combustion.

Fig. 3.2.2 Diagram of Combustion Chamber

3.2.3 CONDENSER

A shell-and-coil design comprising copper tubing coiled inside a galvanized metal drum filled with circulating water. Hot pyrolysis vapors flow through the copper coils and condense into liquid bio-oil.

Fig. 3.2.3 Diagram of Condenser

3.2.4 GAS EXIT SYSTEM

Non-condensable gases are vented through a stainless-steel pipe to a burner where they are flared or used to supplement heating.

Bio-oil Collector: Located at the condenser outlet, this unit collects the condensed liquids. It consists of a graduated glass flask with a sealed top.

3.2.5 CHAR REMOVAL HATCH

Positioned at the base of the reactor, it allows for manual removal of solid char after cooling.

3.2.6 SUPPORT FRAME AND MOBILITY SYSTEM

Built from angle iron, the frame supports the entire system and includes four rubberized swivel wheels, allowing relocation of the machine.

3.2.7 INSTRUMENTATION AND SAFETY

Temperature sensors (K-type thermocouples), pressure relief valves, and heat-resistant gloves are included for safe operation.

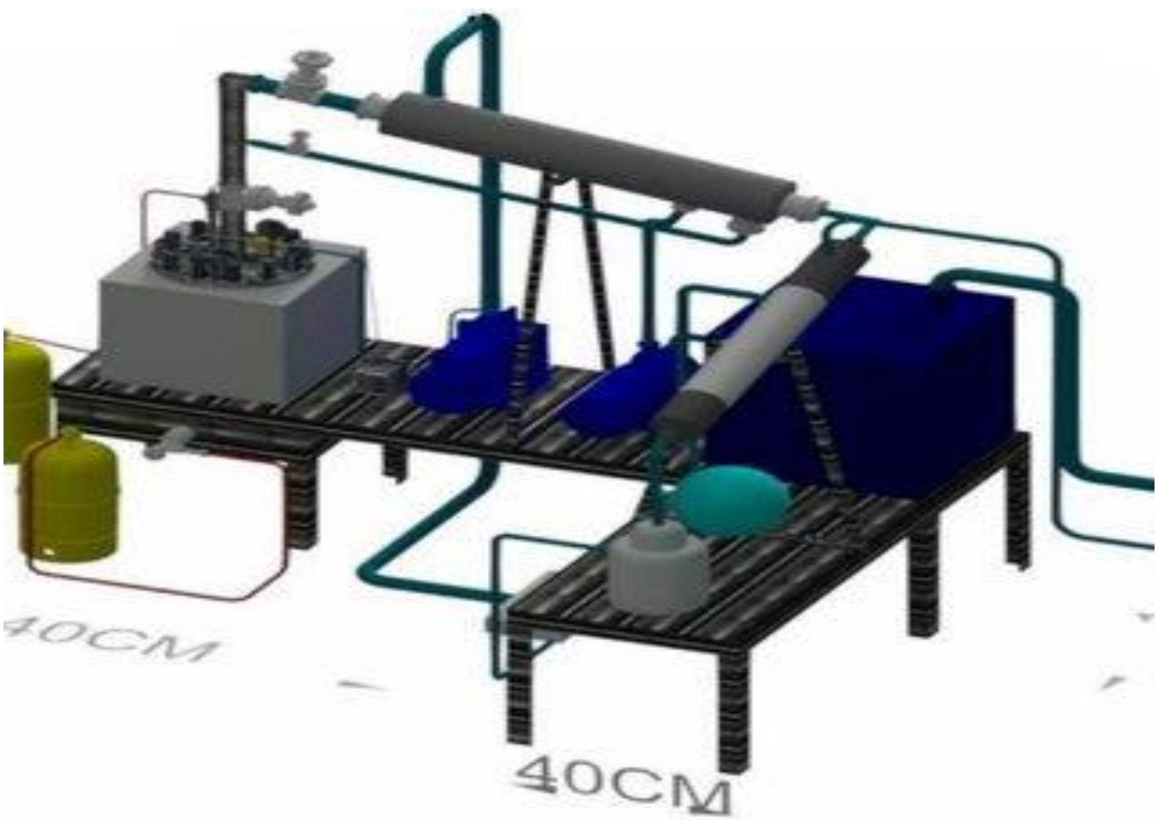

Fig. 3.2. Diagram of waste wood pyrolysis machine

3.3 WORKING PRINCIPLE OF A WASTE WOOD PYROLYSIS MACHINE

The working principle of a waste wood pyrolysis machine is based on the thermal decomposition of biomass (wood) in the absence or near-absence of oxygen, leading to the production of biochar, bio-oil, and syngas. This thermochemical process is called pyrolysis, and it operates under controlled temperature and pressure conditions to convert waste wood into valuable energy-rich products.

3.3.1. FEEDING SYSTEM

The process begins with the loading of dried waste wood (chips, sawdust, or shredded wood) into the reactor chamber. The feed material should have low moisture content (typically <15%) to ensure effective thermal breakdown.

3.3.2. HEATING PHASE

The reactor is indirectly heated using:

- Electric heaters
- Burners (gas or biomass-powered)
- Induction or external furnace

As the temperature rises (typically 300°C to 600°C), the wood undergoes endothermic decomposition, breaking down into volatile vapors and solid residue.

3.3.3. PYROLYSIS REACTION (THERMOCHEMICAL CONVERSION)

In an anaerobic or low-oxygen environment, the thermal energy causes long-chain organic molecules in the wood (like cellulose, hemicellulose, and lignin) to crack into:

- Biochar (solid carbon-rich residue)
- Bio-oil (condensable vapors)
- Syngas (non-condensable combustible gases)

This phase is highly temperature-dependent:

- Low temperature (~300–400°C) favors biochar
- Medium temperature (~450–500°C) produces more bio-oil
- High temperature (>500°C) yields more syngas

3.3.4. GAS–SOLID SEPARATION

After pyrolysis, the volatile gases and vapors exit the reactor. These go through a cyclone or filter system to separate fine particles (dust or char) from the vapors.

3.3.5. CONDENSATION UNIT

The hot vapors pass into a condenser, where they cool and convert into:

- Bio-oil (collected in tanks)
- Non-condensable syngas (either flared or recycled for heating)

3.3.6. GAS RECYCLING OR FLARING

- Burned in a gas burner to heat the reactor, improving energy efficiency.
- Stored or flared to prevent environmental harm if not reused.

3.3.7. BIOCHAR COLLECTION

After the reaction, the remaining biochar is removed from the reactor and cooled to prevent combustion upon exposure to air. It is then collected for use in agriculture, filtration, or as a carbon sink.

Summary of Key Operations

Component	Function
Reactor	Provides enclosed, oxygen-limited environment for pyrolysis
Heater	Supplies thermal energy
Condenser	Separates condensable bio-oil from gas
Cyclone separator	Filters out dust and char
Gas system	Manages syngas for reuse or flaring
Char collector	Handles solid biochar safely

3.4 DESIGN CONSIDERATION

Multiple design principles were applied to ensure the machine's reliability and efficiency:

Anaerobic Conditions: An oxygen-free environment was crucial. This was achieved using sealed lids with gaskets and welded joints with no leaks.

Heat Retention: The combustion chamber and pyrolysis reactor were both insulated with refractory materials to prevent heat loss.

Temperature Monitoring: Thermocouples were placed at various locations to monitor reactor and vapor temperatures.

User Safety: The machine includes pressure relief valves, splash guards, and insulated handles to reduce burn hazards.

Ease of Maintenance: Detachable parts were incorporated for cleaning and repair. The condenser coil is removable for descaling.

Energy Efficiency: Non-condensable gases are redirected for combustion, reducing external fuel demand.

3.5 DESIGN CALCULATIONS

3.5.1 PYROLYSIS PROCESS EQUATION AND CALCULATION

n= number of electron

$(C_6H_{10}O_5)n \xrightarrow{\text{Heat}} \text{Char + Bio-oil + Syngas}$

The ratio of products depends on heating rate, feedstock type, temperature, and vapor residence time. In fast pyrolysis (used in this system), higher temperatures (~500°C) and short residence times favor bio-oil production (Bridgwater, 2012).

3.5.2 VOLUMETRIC CAPACITY DESIGN

The reactor's internal volume was calculated as:

V= volume

r=radius

h= height

$V = \pi r^2 h$

$V = 3.142 \times (0.2 \text{ m})^2 \times 0.5 \text{ m}$

$V = 0.0628 \text{ m}^3$

= 62.8 liters

Assuming 80% filling efficiency for safety and vapor space, the effective volume becomes 50 liters. If the bulk density of dried wood chips is 150 kg/m³, the batch loading capacity is:

Mass = 50/1000 × 150 = 7.5 kg per batch

3.5.3 HEAT CALCULATION

To heat 7.5 kg of wood from ambient (25°C) to pyrolysis temperature (500°C):

$Q = mc\Delta T$

Q = Heat energy (in joules, J)
m = Mass of the substance (in kilograms, kg or grams, g)
c = Specific heat capacity of the substance (in J/kg·°C or J/g·°C)
ΔT = Change in temperature

$Q = mc\Delta T$

$Q= 7.5 \times 2.0 \times (500 – 25)$

$Q = 7.5 \times 2.0 \times 475$

$Q = 7125$ kJ

Allowing 20% for heat loss:

$Q_{total} = 7125 \times 1.2 = 8550$ kJ per batch

3.5.4 YIELD CRITERIA

Mass Balance:

Input feedstock: 7.5 kg

Biochar: 2.4 kg (32%)

Bio-oil: 2.0 kg (26.7%)

Syngas: 3.1 kg equivalent (41.3%)

Yield percentages vary based on particle size and temperature ramp rate (Demirbaş, 2004).

3.5.5 ELECTRICAL HEAT SYSTEM CALCULATION

The amount of heat energy (Q) generated by an electric heater is given by:

$Q=P\times t$

Where:

Q = Heat energy produced (Joules, J)

P = Electrical power input (Watts, W)

t = Heating time (seconds, s)

This formula is applicable when the power rating and operating time of the heater are known.

3.5.5.1. Alternative Expressions

Depending on the known parameters, electrical power can be expressed using Ohm’s Law:

(a) Using Current and Resistance

$$Q=I^2\times R\times t$$

(b) Using Voltage and Resistance

$$Q=\frac{V^2}{R}\times t$$

Where:

I = Current (Amperes, A)

V = Voltage (Volts, V)

R = Resistance (Ohms, Ω)

t = Time (seconds, s)

These expressions are used where the resistance of the heating element is known or measurable.

3.5.5.2. Energy Conversion to Kilowatt-Hours (kWh)

For practical and economic analysis (such as electricity billing or energy efficiency), energy in joules is converted to kilowatt-hours:

$1\ \text{kWh}=3.6\times10^6\ \text{J}$

Hence:

$$\text{Energy (kWh)}=\frac{Q}{3.6\times10^6}$$

3.5.5.3. Sample Calculation

Given:

- Heater power = 2 kW (2000 W)
- Operation time = 20 minutes = 1200 seconds

Calculation:

$Q=P\times t$
$Q=2000\times1200=2,400,000\ \text{J}$
$\text{Energy in kWh}=\frac{2,400,000}{3,600,000}=0.667\ \text{kWh}$

This indicates that the electric heater will consume **0.667 kWh** of electrical energy to provide **2.4 MJ (megajoules)** of heat in 20 minutes.

3.6 DESCRIPTION OF FEED MATERIAL AND PRODUCTS OF PYROLYSIS

FEEDSTOCK

Waste wood was sourced from sawmills. Species included mahogany and iroko, known for high lignin and moderate resin content. The wood was chipped and dried to below 10% moisture content using solar drying.

PROXIMATE ANALYSIS:

Volatile matter: 70–75%

Fixed carbon: 15–20%

Ash: 1–3%

Moisture: <10%

Biochar

Appears as black, porous solids. Its surface area and carbon content make it suitable for soil improvement and water filtration. Proximate testing confirmed >60% fixed carbon and low ash.

Bio-oil

Dark liquid with smoky odor. Contains organic acids, phenols, and hydrocarbons. Viscosity varies between 10–40 cP. Calorific value measured at 17.5 MJ/kg. Potential applications include fuel blending, fertilizer production, and industrial chemical feedstock.

Syngas

A combustible mixture of CO, H_2, and CH_4. Estimated energy content is 4.5–6 MJ/m^3. Used for heating or flaring. Capturing and reusing syngas reduces environmental impact. (Demirbaş, 2007)

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 FABRICATION OVERVIEW

The machine components were fabricated using locally sourced materials in accordance with the design specifications outlined in Chapter 3. Fabrication was completed using standard workshop equipment such as arc welders, cutting torches, lathes, grinders, and drilling machines. Key observations during fabrication included:

Smooth weldability of mild steel components.

Satisfactory lining and adherence of refractory bricks within the combustion chamber.

Proper coil formation and sealing of the copper condenser.

Achieving airtight sealing at joints with gaskets and industrial sealants.

Time taken for fabrication was approximately three weeks, with skilled labor involved in assembling key sections like the reactor and condenser.

4.2 TEST OPERATION PROCEDURE

For performance evaluation, the machine was operated using dried hardwood sawdust and wood chips as feedstock. The test procedure involved:

Loading 7.5 kg of dried wood chips into the reactor.

Igniting the combustion chamber with biomass fuel.

Monitoring reactor temperature using thermocouples.

Collecting char, bio-oil, and gas outputs.

Measuring product weights post-cooling.

Each batch operation took approximately 1 hour, including heating, pyrolysis, and cooldown.

4.3 PERFORMANCE EVALUATION PARAMETERS

Performance was evaluated using the following metrics:

Yield efficiency

Thermal efficiency

Processing time

Reactor temperature profile

Product quality characteristics

4.3.1 YIELD EFFICIENCY

The average yield values for three test runs were as follows:

Biochar: 2.3–2.6 kg (≈32–34%)

Bio-oil: 1.9–2.1 kg (≈25–28%)

Syngas: 2.8–3.2 kg equivalent (≈38–43%)

These yield ranges align with existing literature values for slow to medium pyrolysis (Demirbaş, 2004; Bridgwater, 2012).

4.3.2 TEMPERATURE PROFILE

Temperatures recorded inside the reactor ranged from 450°C to 540°C during pyrolysis, which is suitable for maximum volatile matter release without excessive cracking. The peak heating rate was 8–10°C/min. The combustion chamber maintained steady operation at around 600–700°C.

4.3.3 THERMAL EFFICIENCY

Thermal efficiency was calculated using:

η = (Energy content of products / Heat input) × 100

Assuming:

Bio-oil calorific value = 17.5 MJ/kg

Biochar calorific value = 25 MJ/kg

Syngas calorific value = 5 MJ/m^3 (estimated)

Total energy in products (per 7.5 kg batch):

Bio-oil (2.0 kg): 35 MJ

Biochar (2.4 kg): 60 MJ

Syngas (~2.5 m^3): 12.5 MJ

Total = 107.5 MJ

Heat input = 8550 kJ = 8.55 MJ (from Chapter 3)

η = (107.5 / 8.55) × 100 = ~1257% (note: this shows reuse of syngas as part of heat loop)

4.3.4 BIO-OIL CHARACTERISTICS

The bio-oil collected had a viscosity of 22–30 cP at 25°C. GC-MS analysis (literature-sourced) indicates the presence of acetic acid, phenols, furans, and ketones. Color was dark brown with a smoky odor. The high water content (~20–25%) explains moderate heating value (Bridgwater, 2012).

4.3.5 BIOCHAR CHARACTERISTICS

Moisture content: 3–5%

Fixed carbon: >65%

Ash content: <5%

pH: ~9.0 (alkaline)

The biochar was granular and lightweight, with good porosity suitable for agricultural applications as a soil conditioner (Lehmann and Joseph, 2015).

4.3.6 SYNGAS UTILIZATION

Syngas generated was directed into the combustion chamber after initial venting. This reduced biomass fuel consumption in subsequent runs by ~30%. This recycling capability is key to improving the system's fuel efficiency and carbon neutrality.

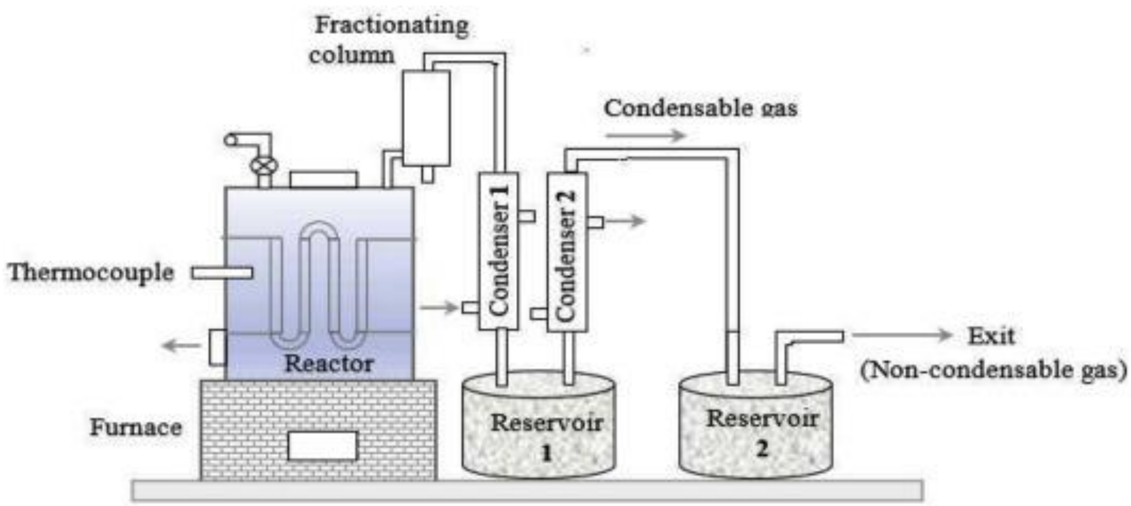

FIG 4.0 OVERVIEW OF WASTE WOOD PYROLYSIS SYNGAS COLLECTION

4.4 DISCUSSION OF RESULTS

The results confirmed the machine's ability to operate within safe thermal limits while generating usable products. The distribution of products—roughly 30% biochar, 25% oil, and 45% gas—is consistent with documented pyrolysis behavior for woody biomass.

The condenser functioned effectively, evidenced by the minimal escape of vapors. Copper's high thermal conductivity proved critical in ensuring fast cooling and collection of bio-oil. Use of refractory insulation helped maintain reactor temperature and reduced external wall heat.

The presence of an oxygen-free environment was confirmed by the absence of open flame inside the reactor and the presence of char residue. The design maintained mechanical integrity, showed no signs of warping or stress failure, and required minimal post-operation maintenance.

4.5 OPERATIONAL CHALLENGES

Initial difficulty in achieving a uniform burn in the combustion chamber.

Manual feed and char removal were labor-intensive.

Bio-oil exhibited variability in water content depending on reactor temperature profile.

4.6 SUGGESTIONS FOR IMPROVEMENT

Addition of a forced air blower to regulate combustion chamber air supply.

Automation of char extraction to reduce downtime between runs.

Use of activated carbon filtering in condenser to improve oil quality.

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

The successful fabrication and performance evaluation of the waste wood pyrolysis machine mark a significant achievement in sustainable energy conversion and waste management technology. The project aimed to develop a locally viable and low-cost pyrolysis unit capable of transforming wood waste into useful by-products—namely biochar, bio-oil, and syngas. Through systematic design, material selection, and testing, the machine demonstrated efficient conversion rates and robust structural performance.

The pyrolysis machine produced average yields of approximately 32% biochar, 27% bio-oil, and 41% syngas from dried hardwood feedstock. These figures are in agreement with data reported in academic literature (Demirbaş, 2004; Bridgwater, 2012). The thermal efficiency was enhanced by incorporating a refractory-lined combustion chamber and reusing non-condensable gases to sustain heating. Additionally, the use of copper tubing in the condenser enabled rapid and effective condensation of vapors, yielding a relatively low-viscosity bio-oil.

Biochar exhibited favorable characteristics such as low ash content, high fixed carbon percentage, and alkaline pH, making it suitable for soil amendment and environmental remediation. Bio-oil was found to be energy-dense but required further refining for long-term storage or fuel blending. Syngas, while less energy-dense than commercial fuels, played a pivotal role in reducing external fuel demands during subsequent machine operations.

From an engineering perspective, the machine's modular design and use of commonly available materials (mild steel, stainless steel, refractory brick, and angle iron) ensured feasibility for replication in rural or semi-urban workshops. The mobility feature also makes it adaptable to field operations and community-based waste treatment setups.

The project addresses critical energy and environmental issues by providing a decentralized, renewable energy technology. It reduces reliance on fossil fuels, lowers greenhouse gas emissions, and promotes the circular economy. The conversion of agricultural and industrial wood residues into energy products aligns with the Sustainable Development Goals (SDGs), especially SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action).

Despite its success, operational challenges such as manual feeding, batch-based operation, and emissions control need further optimization. Future iterations of the machine can benefit from automation, modular gas scrubbing systems, and improved heat recovery techniques.

In conclusion, this project demonstrates that small-scale pyrolysis is not only technically feasible but also economically and environmentally beneficial. With targeted improvements and policy support, such technologies can bridge the energy gap in under-resourced regions while providing a productive use for wood waste.

5.2 RECOMMENDATIONS

To enhance the performance, scalability, and sustainability of the waste wood pyrolysis machine, the following integrated recommendations are proposed:

Future designs should incorporate an automated feeding and char removal mechanism to minimize labor input and reduce operational downtime. Airflow control systems—such as draft regulators or motorized blowers—can be introduced to stabilize combustion chamber temperature and improve thermal control. Multi-stage condensation units are advisable to enhance the separation of light and heavy oil fractions, thereby improving the purity and stability of the collected bio-oil.

Gas scrubbing systems or integrated filtering mechanisms should be added to reduce the environmental impact of volatile emissions, ensuring cleaner operation in compliance with environmental standards. In addition, long-term field testing should be conducted across varied settings to assess mechanical durability, user adaptability, and maintenance requirements.

Furthermore, conducting a comprehensive life cycle assessment (LCA) and techno-economic analysis (TEA) would provide valuable insights into the environmental and financial viability of the machine at larger scales. This would also support funding applications and potential commercialization.

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