Research Article / Review Article

FUPRE JOURNAL 9(4):211-221(2025)
DOI: /10.60787/FJSIR.v9i5.211-221

FUPRE Journal

of

Scientific and Industrial Research

ISSN: 2579-1184(Print) ISSN: 2578-1129 (Online)

http://fupre.edu.ng/journal

Development of a Pyrolysis Machine for Bio-Char Production

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ARTICLE INFO

Received: 23/07/2025
Accepted: 07/12/2025

Keywords

Bio char, Biomass conversion, Oil palm empty fruit bunches, Pyrolysis, Thermal decomposition

ABSTRACT

The rising demand for sustainable waste control and renewable power has driven interest in the use of thermochemical conversion technologies like pyrolysis as a means of biomass waste valorisation. This study presents a conceptual design, construction, and assessment of a pyrolysis machine developed to convert biomass, particularly oil palm empty fruit bunches (OPEFB) into biochar. The pyrolysis machine operates as a metallic reactor enclosed inside a thermally insulated housing, supported with the aid of a custom-built heating unit, gas collection setup, pressure relief mechanism, and a control panel for secure and optimised operation. The machine is designed for batch processing, while the reactor functions under low-oxygen environment and includes adjustable temperature settings to optimise product yields. Experimental trials on the machine confirmed the system's effectiveness, achieving average yields of 68% biochar, 12% bio-oil, and a syngas rich in flammable gases. The pyrolyser operated efficiently, ingesting 10.8 kW of power, and proved to be structurally reliable and user-friendly. Overall, the developed pyrolysis machine presents a practical and environmentally friendly technique to organic waste valorisation and energy recovery, offering a sustainable solution to the demanding waste disposal problems and contributing to the circular economy.

1. INTRODUCTION

The global push for sustainable development in recent decades, has increased the need for solutions that can solve different environmental and climate demanding issues. Among those challenges are biomass wastes management, climate change, and soil degradation, especially in developing areas. One innovative solution that addresses the aforementioned issues is pyrolysis, a thermochemical process that converts biomass and its wastes into valuable by-products, that includes bio char, bio-oil, and bio-gas, under low oxygen environment. Pyrolysis does not only present itself as a sustainable solution for waste management but also offers economic and environmental benefits for communities and individuals.

The products (bio char, bio-oil, and bio-gas) derived from pyrolysis serves different valuable functions. Bio char is a porous, carbon-rich material that enhances soil

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DIO: /10.60787/FJSIR.v9i5.211-221
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fertility, keeps nutrients and moisture, immobilizes heavy metals, and performs a vast role in carbon sequestration, thereby helping to mitigate climate change (Lehmann and Joseph, 2012). Bio-oil, a dark viscous liquid, serves as a renewable substitute for fossil fuels in combustion engines and industrial heating (Bridgwater, 2012). Syngas, which is a mixture of gases like carbon monoxide and hydrogen, can be used to generate energy (Tang and Huang, 2005; Yue *et al.*, 2023). All these products offer a proper way to manage agricultural wastes, reduce the impact of traditional disposal strategies such as burning on the environment, while promoting the technology of renewable energy (Mohan *et al.*, 2006; Bridgwater, 2012; Vuppaladadiyam *et al.*, 2022).

There are different biomass feed stocks available which include oil palm empty fruit bunches, coconut husks, rice husks etc. However, the oil palm empty fruit bunch (OPEFB) stands out due to its high availability and its underutilisation. The global palm oil enterprise, especially in nations such as Indonesia, Malaysia, Nigeria, and Thailand, produces tens of millions of tons of OPEFB yearly. According to Anuar *et al.* (2019), approximately 22–23 million metric lots of OPEFB are generated every year in Malaysia, with approximately 70% of the OPEFB received at some point of the processing of fresh fruit bunches. The OPEFB is frequently disposed through open dumping or burning practices, which contribute to air pollution, land degradation, and greenhouse gas emissions (Anyaoha and Zhang, 2023).

The OPEFB consists of cellulose (40–65%), hemicellulose, and lignin. These chemical composition makes it a great material for thermochemical conversion methods (Hossain *et al.*, 2016; Said et al, 2021). Its fibrous and cumbersome shape also makes it suitable for pyrolysis, as its bio char possesses good absorption capabilities containing a high carbon material (Tan *et al.*, 2022). Researches have also affirmed that OPEFB-derived bio char is effective for soil remediation, specifically in reducing the mobility and bioavailability of heavy metals like lead, cadmium, and arsenic (Ahmad *et al.*, 2014). Furthermore, OPEFB fibres can be processed into a wide range of materials such as composite boards, insulation panels, bio plastics, and construction components (Shakir *et al.*, 2024; Waluyo *et al.*, 2024; Wahida and Ghazi, 2015), which adds to the its economic chain. The valorisation of OPEFB, consequently aligns flawlessly with the concept of circular economy, where waste is not simply disposed of, but transformed into assets that can re-input the production and intake cycle.

Despite the validated usefulness of the pyrolysis technology, its adoption in developing nations remains constrained due to some numerous obstacles. These includes the high capital costs of industrial-scale pyrolysis equipment, technological complexity, inadequate technical know-how, and a lack of supportive infrastructure for cottage systems (Bridgwater, 2012; Scholz *et al.*, 2014). As a result, the advantages of biomass valorisation through pyrolysis are regularly inaccessible to small-scale farmers, entrepreneurs and community cooperatives, who stand to benefit the most from such

innovations. To address these barriers, this study aims to develop a small-scale, low-cost, and energy-efficient pyrolysis machine using locally sourced materials and simple engineering techniques. The specific emphasis of the design is on thermal optimisation to ensure steady pyrolysis at optimum temperatures, ensures a user-friendly operation for individuals without little technical knowledge, environmental management mechanisms consisting of adequate gas venting and insulation, affordability and portability, making it suitable for deployment in rural and peri-urban areas. This localised solution helps grassroots innovation, youth empowerment, and entrepreneurship in bioenergy manufacturing whilst presenting a cheap solution for managing agricultural waste.

The outcome of this research not only reduces environmental pollution, but also creates economic value, promotes energy independence, and improves soil health through bio char application. The outcomes of this project are expected to have extensive implications for agriculture, environmental remediation, sustainable energy production, and climate resilience in regions going through both biomass overabundance and power shortage.

2. MATERIALS AND METHODS

2.1 Materials Collection and Preparation

The pyrolysis machine fabricated in this research was designed as a batch-type unit, which ensures efficient thermal conversion of the biomass. The major materials used for its construction are mild steels sheets, insulation materials, heating elements and digital control component, sourced from suppliers and metal markets in Ibadan, Oyo State, Nigeria. The reactor chamber of the pyrolysis machine was constructed using 5mm thick mild steel for both the inner and outer cylindrical chambers of the machine, chosen for its durability and thermal resistance. The insulating material is fibreglass, inserted between the inner and outer chamber walls to minimise heat loss and improve energy efficiency during operation. More so, the heating system of the machine has a capacity of 10.8kW and it was designed to support controlled pyrolysis at the temperature reaching up to 1000°C.

The biomass used to test the machine, Oil palm empty fruit bunches (OPEFB), were sourced from a commercial plantation in Arulogun, Ibadan. This agricultural waste was selected due to its availability and potential thermal conversion to yield a number of valuable products.

2.2 Design Analysis

The pyrolysis machine's design ensured durability, strength, thermal efficiency, user-friendly and operational safety. The major component parts were designed as follows:

Enclosure (Housing) – Outer Casing and Protection Shell

The enclosure (housing) serves as the machine's shell, which houses all the machine's internal components like the reactor chamber, heating coils, etc. It provides the machine with structural support and prevents heat loss with the aid of the insulation system. A modular design approach was adopted to facilitate scalability

and enable easy replacement of components, ensuring long-term operational sustainability.

The enclosure chamber is cylindrical, and below are its dimensions and considerations;

- Outer Diameter (Do): 609.6 mm
- Inner Diameter (Di): 527.09 mm
- Height (h): 704.85 mm
- Thickness (t): 38.1 mm

The volume of the outer and inner cylinders was calculated to decide the wall quantity, which is vital for assessing cloth thickness and heat insulation desires.

Outer Cylinder Volume (V_{outer}):

$$V = \pi \times r\text{^}2 \times h = 3.14 \times 304.822 \times 787.4 = 229.70l \quad (1)$$

Inner Cylinder Volume (V_{inner}):

$$v = 3.14 \times 263.54522 \times 787.4 = 171.30l \quad (2)$$

Void Volume:

$$V_{ins} = V_{outer} - V_{inner} = 229.70 - 171.30 = 58.4l \quad (3)$$

Reactor Chamber

The reactor chamber is placed inside the enclosure chamber; it houses the biomass for pyrolysis. Constructed from mild steel, it is designed to withstand elevated temperatures and prevent oxygen infiltration, which could otherwise trigger combustion rather than thermal decomposition.

The chamber is also cylindrical with the following dimensions;

- Outer Diameter (Do): 260.35 mm
- Height (h): 704.85 mm

The volume of the reactor chamber was calculated to determine the available space for biomass.

Reactor Volume ($V_{reactor}$):

$$v = \pi \times r2 \times h = 3.14 \times 130.1752 \times 704.85 = 37.8l \quad (4)$$

Material Strength:

The material strength of the mild steel used was estimated using the hoop stress formula to ensure resistance to pressure.

Hoop Stress (σh):

$$\sigma h = (P \times D)/(2 \times T) = (4053 \times 527.05)/(2 \times 38.1) = 28.03\text{kPa} \quad (5)$$

Where;

- T is the thickness,
- D is the inner diameter,
- P is the inner pressure gotten from combined law gas.

Given the yield strength of the mild steel as between 200MPa and 350MPa, the calculated hoop strain (28.03 kPa) is below the yield strength of mild steel (200-350 MPa), confirming the material's suitability.

Insulation Section

The insulation section was essential for minimising heat loss during the machine operation. A fiberglass insulation layer surrounds the reactor chamber to significantly reduce thermal losses, thereby improving process efficiency.

Fiberglass was used due to its low thermal conductivity (K = 0.04 W/m•K) and it occupies the 38.1 mm gap between the outer and inner chamber.

Thermal Resistance (R):

$$Thermal\ Resistance\ (R): \frac{In(D_o \div D_i)}{2\pi KL} = \frac{In(609.6 \div 527.05)}{2\pi \times 38.1 \times 0.04} = 0.01519°c \quad (6)$$

Where;

- R is the thermal resistance
- Do and Di are the outer and inner diameters, respectively.
- K is the thermal conductivity of the insulation (fibre glass)
- L is the thickness of the insulation

Heating Section

The heating section consists of six heating coils, each with a power rating of 1800 W, supplying a total power 10.8 kW. Six electric heating coils were symmetrically placed around the chamber to ensure uniform heat distribution during pyrolysis.

The coils were designed to heat the reactor chamber to the target temperature of 1,000°C.

The rate of the heat transfer through the cylindrical wall was calculated to ensure efficient heating.

$$Heat\ Transfer\ (Q): \frac{2\pi LT(T_1 - T_2)}{In(\frac{r2}{r1})} = \frac{2 \times 3.14 \times 0.04 \times 787.4(1000 - 25)}{In(\frac{263.525}{304.8})} = 1.326.03W \quad (7)$$

Where;

- K is the thermal conductivity of the insulation
- L is denoted as chamber height
- The inner and outer radii as r^1 and r^2
- The target temperature and starting temperature are T_1 and T_2

Control Panel

The control panel was attached to the machine support. It facilitates precise temperature regulation, real-time pressure monitoring, and safe operational control. It also incorporates a switch for the pressure release valve and an emergency shut-off function.

It regulates the temperature and monitors pressure during operations. It is designed to handle a current of 49.9A and consume 10.8 kW of power.

$$Current\ (I): \frac{P}{V} = \frac{10,800}{220} = 49.09A \quad (8)$$

Where;

- I is the current in amperes (A)

- P is the power in watts (W)
- V is the voltage in volts (V)



(a) **(b)**

Figure 1: The pyrolyser (a) The front view/inner view (b) The side view

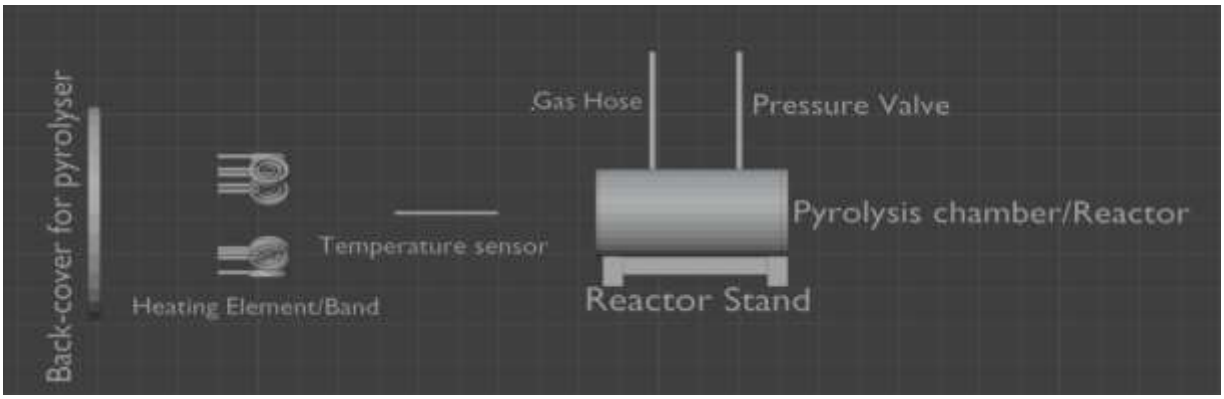


Figure 2: *The inner components of the pyrolyser*

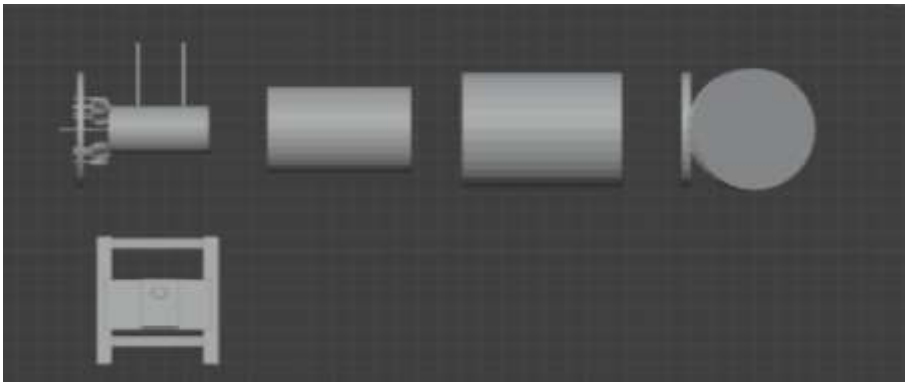


Figure 3: *Exploded View of the Machine*

Machine Construction

The fabrication process involved several stages:

1. Rolling and Shaping Mild Steel: The fabrication process starts with cutting and shaping the mild steel into the desired shape of the different components. The mild sheets were cut and rolled into cylindrical shapes to give the enclosure chamber 609.6mm diameter) and the reactor chamber (260.35mm diameter).
2. The Chamber Construction and Insulation: The rolling and shaped mild steel were positioned appropriately into each other to give the desired machine, where the reactor chamber is inside the enclosure chamber. However, the enclosure chamber was double-layered, with the insulation material (fiberglass) packing between the 38.1mm interstitial space. The layered space of the enclosure chamber was sealed to prevent bridging and reduce heat retention during the operation.
3. Support System Construction: Structural integrity was achieved through the fabrication of a welded steel support stand, which was cautiously aligned and attached to the reactor base. The layout incorporated plates at crucial joints to provide extra stability against operational vibrations and thermal expansion forces.
4. Drilling Holes for Gas and Pressure Release: The pressure management system required precision drilling of two ports; a gas collection outlet placed on the chamber's apex and a pressure relief passage ready with a calibrated safety valve. Both capabilities were engineered to maintain safe working conditions throughout thermal processing.
5. Electrical Setup: The electrical setup consists of the heating coils installed in a circumferential pattern around the reactor chamber, connected to the control panel (where pressure or temperature is regulated). This integration aids in the proper wiring of the machine, where the coils are well connected, and all necessary components are connected to the control panel and the switch.
6. Final Assembly and Testing: Final commissioning include the complete system verification, beginning with pneumatic pressure testing of the machine to validate structural integrity, followed by the thermal cycling to confirm proper heat distribution and manage machine responsiveness. All protection interlocks and emergency shutdown protocols have been carefully tested before operational deployment.

Fabrication Parameters

Table 1 summarizes the fabrication parameters of the pyrolysis machine. These parameters encompass each component's dimensions, substances, and key layout considerations.

Table 1: Fabrication Parameters of the Pyrolysis Machine

S/N	Machine Components	Material Description
1	Outer chamber	Mild steel, Dimension: 762mm × 609.6mm

2	Pyrolysis chamber/Reactor	Mild steel, Dimension: 457.2mm × 254mm
4	Pyrolysis chamber stand	Iron rod, Dimension: 127mm × 50.8mm
5	Heater bands	Cooking ring
6	Electrical Box	Metal, Dimension: 203mm × 101.6mm
7	Machine stand	Iron rod, Dimension: 762mm × 609.6mm

Testing and Performance Evaluation

The pyrolysis machine was tested with the OPEFB for the production of bio-char, bio-oil, and biogas.

3. RESULTS AND DISCUSSION

The constructed pyrolyser is as shown in Figure 4.



Figure 4: Fully assembled pyrolysis machine ready for testing

Performance evaluation

The performance of the machine was evaluated by producing biochar and bio-oil from oil palm empty fruit bunches. The machine was evaluated in three runs and OPEFB were pyrolyzed at 350^0C for 2 h. An average yield of 68±2 % biochar, 12% bio-oil, and a syngas rich in flammable gases were obtained from the pyrolysis. A facility to collect gas from the operation may be included at a later stage**.**

The flow diagram of the operation is as shown below:



Figure 5: Performance evaluation showing pyrolysis process and products

Cost Analysis

The cost analysis of the pyrolyser is presented in Table 2.

Table 2: Cost Analysis of the Pyrolysis Machine

S/N	MATERIAL	SPECIFICATION	QUANTITY	AMOUNT
1	Mild Steel sheet	3mm thickness	2 sheets	50,000
2	Electrode	Gauge 12	1 pack	3,500
3	Cutting Disc	Flexovite	2 pieces	1,500
4	Grinding Disc	Powerflex	2 pieces	2,000
5	Hinges		2	5,000
6	Fiber Glass		½ sack	10,000
7	Paint	Black and Grey	2	20,000
8	Varnish		1	8,000
9	Connectors		12	12,000
10	Heat Resistance Cable		1	9,000
11	Contactor		1	10,000

12	Indicator Lamp		2	2,000
13	Off and On Switch		1	2,000
14	Circuit Breaker		1	8,000
15	Thermocouple		1	8,000
16	Circuit Box		1	15,000
17	Cable Plug	4mm, 15A	1	3,000
18	Railings and internal wiring cable			3,000
19	Single flex		1	12,000
20	Workmanship			50,000
	Total			**234,000**

4. CONCLUSION

The pyrolysis system fabricated converts biomass, oil palm empty fruit bunches (OPEFB) into bio char, bio-oil, bio-gas which demonstrated the machine's efficiency. The pyrolysis's structure which includes the mild steel for sturdiness and fibreglass for insulation ensured the retention of the thermal heat to protect the machine during operation. The machine consumes 10.8kW and the heating elements were operated at a maximum temperature of up to 1000°C which aid a proper and saturated pyrolysis operation.

This research has developed an efficient pyrolysis machine for converting biomass into bio char, bio-oil and bio-gas. It has effectively converted oil palm empty fruit bunches, and is expected efficiently handle other biomass and agricultural wastes. The pyrolysis system is affordable for a small-scale application and provides a more sustainable and circular economic system by turning wastes into valuable products. The constructed machine has the tendency of scalability and can be replicated to advanced system and larger applications. The solution provided by this system contributes to the United Nations Sustainable Development Goals (SDGs), especially SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action).

Declaration: The authors declare no conflict of interest.

Funding: No funding was received for this study.

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