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Development and Performance Evaluation of a Plastic and Biomass Torrefaction Machine

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Abstract

The increasing demand for sustainable energy solutions and effective waste management strategies has driven the development of innovative technologies to address plastic pollution and biomass utilization. This study presents the design, fabrication, and performance evaluation of a plastic and biomass torrefaction machine. The machine, developed using locally sourced materials, integrates key components such as a barrel, screw conveyor, die, hopper, electric motor, and heating element to convert low-density polyethylene (LDPE) and rice husks into high-energy, torrefied products. The torrefaction process was optimized at varying temperatures (270°C to 300°C), with performance metrics including moisture content, calorific value, ash content, volatile matter content, and fixed carbon content evaluated using standardized methods. Results revealed a significant improvement in energy density and material stability as the temperature increased, with the highest calorific value (8,337.35 kJ/kg) and lowest moisture content (0.39%) achieved at 300°C. The machine demonstrated efficiency in reducing moisture and enhancing the fixed carbon content, producing environmentally friendly, high-energy fuels suitable for energy generation applications. This study highlights the potential of the torrefaction machine as an eco-friendly solution for managing plastic and biomass waste while promoting renewable energy generation. Recommendations include scaling the machine for industrial applications and further optimizing its design to accommodate diverse feedstock types. The innovation addresses critical environmental challenges, contributing to sustainable waste management and energy production efforts.

Keywords: Low-density Polyethylene (LDPE), Biomass, Rice Husk, Torrefaction Machine, Temperature, Sustainable Energy, Efficiency

1.0 Introduction

The development of sustainable energy solutions has driven interest in biomass utilization, especially through torrefaction—a thermal process that enhances the energy density and stability of biomass materials. Torrefaction is a mild pyrolysis process typically conducted at temperatures between 200°C and 300°C under low-oxygen conditions, effectively transforming biomass into a renewable fuel with improved combustion properties. This process is especially beneficial in converting waste biomass, such as agricultural residues and plastics, into valuable energy resources, aligning with the growing need to manage waste efficiently and reduce environmental pollution (Ani et al., 2022; Chen et al., 2021). In Nigeria, where plastic waste accumulation and biomass waste from agriculture are prevalent, developing localized torrefaction technology can provide an efficient method to convert waste into energy, thus addressing both waste management and energy challenges.

A torrefaction machine operates through a series of mechanisms, including heating units, drying chambers, and material handling systems, which are designed to maintain precise temperature control and minimize oxygen infiltration. Such technology not only enhances the calorific value of biomass and plastic but also reduces its moisture content, making it more suitable for fuel applications. While other drying and pyrolysis methods are available, they are often costly, complex, and imported from countries with advanced manufacturing infrastructure, making them unsuitable for many small- and medium-scale industries in developing economies. Thus, this study focuses on the development of a locally sourced, cost-effective torrefaction machine designed to convert plastic and biomass waste into an energy-dense solid fuel. This machine integrates easily into various biomass production processes, including the production of pelletized fuel for energy generation (Ani et al., 2023; Madu et al., 2018).

Previous research has documented various machine designs for biomass drying and torrefaction processes, though these designs are often limited by their inability to handle mixed feedstocks like plastic and biomass concurrently. Integrating plastic into the torrefaction process not only contributes to efficient waste reduction but also allows for the production of higher-energy-content fuels that could support industrial energy demands. Current torrefaction machines are typically designed for either biomass or plastic; hence, there is a critical gap in technology that can accommodate both materials in a single, efficient system, adaptable to local conditions and needs (Nwobodo et al., 2021).

In this context, the study aims to design, fabricate, and evaluate the performance of a hybrid plastic and biomass torrefaction machine. The performance of the machine will be measured by assessing its energy efficiency, throughput, and suitability for large-scale applications. Additionally, it will address key design challenges, including the maintenance of an oxygen-free environment, effective material handling, and precise temperature regulation. Through this development, the study hopes to contribute to the improvement of local recycling and energy systems, reducing the reliance on imported machinery and supporting Nigeria’s transition towards sustainable energy production (Ani et al., 2020).

1.1 Objectives and Scope of Study

The specific objectives of this study are:

- To design and fabricate a torrefaction machine capable of processing both plastic and biomass.
- To evaluate the performance of the machine, focusing on its energy efficiency and the quality of the torrefied materials.

1.2 Justification

The growing accumulation of plastic waste and the underutilization of biomass resources highlight the need for innovative technologies that can simultaneously address waste management and energy production. A plastic and biomass torrefaction machine offers a promising solution by converting waste into valuable energy-dense products. This not only reduces the environmental burden of waste disposal but also creates new opportunities for energy generation, particularly in regions with limited access to conventional energy sources (Innocent Ani et al., n.d.). Additionally, the development of locally manufactured torrefaction machines can contribute to job creation and the growth of the waste-to-energy industry in developing countries.

2.0 Design Analysis And Specifications Of The Plastic and Biomass Torrefaction Machine

2.1 Design Concepts and Considerations

1. The plastic and biomass torrefaction machine were designed to thermally treat waste plastic and biomass materials in a controlled environment to remove volatile compounds without causing complete combustion or melting. This ensures the production of high-quality torrefied materials that can be efficiently used for energy generation and other applications such as biochar production.
2. The design incorporates a mechanical control system for regulating the process temperature and shaft speed, rather than relying on more expensive electronic systems. This approach significantly reduces the overall cost of the machine while maintaining adequate control over the torrefaction process, making the machine affordable for small-scale and informal sector operators.

These considerations ensure the machine is cost-effective, easy to operate, and capable of producing consistent results in terms of biomass and plastic torrefaction quality.

2.2 Determination of the Speed of the Shaft

The system requires a shaft, coupling and a geared motor for a low-speed transmission.

Below is a relationship used to determine the transmitted speed according to Khurmi and Gupta 2012

$$G = \frac{N_a}{N_b} \quad (1)$$

N_a=motor speeds in r.p.m, N_b = speeds of shafts r.p.m, G = gear ratio

2.3 Shaft Design Analysis

i) Shaft subjected to twisting moment only

Torsion equation $\frac{T}{j} = \frac{c\theta}{l}$ (2)

Where T = torsional shear stress, c = modulus of rigidity for the shaft material, j = polar moment of inertia of the shaft, l = length of the shaft

$\theta = Angleoftwistinradian$ (ASME 1995)

Polar moment of sound solid shaft, J = $\frac{\pi}{32} d^4$ (3)

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$$\frac{T}{\left(\frac{\pi}{32}xd^4\right)} = \frac{f_t}{\frac{d}{2}}, wherer = \frac{d}{2} \qquad (4)$$

$$T = f_t x \frac{\pi}{32} x d^4 x \frac{2}{d} \qquad (5)$$

$$T = f_t x \frac{\pi}{32} x d^3 \qquad (6)$$

Twisting moment, T can be obtained from P = $\frac{2\pi NT}{60}$ (7)

ii) Shaft subjected to bending moment only bending equation is given by

$$\frac{M}{l} = \frac{f_b}{y} \qquad (8)$$

Where, M = bending moment, I= moment of merits of cross-sectional area of the shaft about axis of rotation, fb = bending stress, y = distance from neutral axis to outer most fibre

But, I = $\frac{\pi}{64}xd^4$ (9)

Then M = $\frac{f_b}{y}xI$ (10)

M = $\frac{f_b}{y}x\frac{\pi}{64}xd^3$ (11)

but y = $\frac{d}{2}$

M = $\frac{\pi f_b}{32}xd^3$ (12)

Also bending moment equation is given by M = w x L

But for a shaft at tangential or perpendicular, the bending moment is negligible because there is no load impact on the shaft, the force acting on it is compressive/angular.

2.3.1 Determination of Shaft Diameter

The diameter, d of the torrefaction extruder machine transmission shafts was determined from the maximum stress relations given by Okwuchukwu*et al.*, 2022 as:

$$d = \left[\frac{16}{\pi\tau}\sqrt{(k_b m_b)^2 + (k_t m_t)^2}\right]^{1/3} \qquad (13)$$

But equivalent maximum twisting moment is given as

$$T_e = \frac{\pi}{16} x\tau x d^3 = \sqrt{M^2 + T^2} \qquad (14)$$

2.3.2 Selection of Electric Motor for the Torrefaction Machine

The power required to drive the machine is determined as

P = Tω, Where p = power, T= torque and ω = angular velocity but ω = $\frac{2\pi N}{60}$, Where, N= speed of machine.

$$P = \frac{2T\pi N}{60} \quad (15)$$

$$T = \frac{\pi}{16} x d^4 x f_t \quad (16)$$

Where ft = shear stress (torsional)

2.3.3 Extruder Output (Throughput)

Determine the desired throughput or production rate of the extruder system.

Throughput (T) is related to the screw speed by the equation

$$T = \frac{M}{t} \quad (17)$$

Where:T = Throughput (kg/hr), M = Mass of biomass processed (kg) and t = Time taken to process the mass (hr).

3.0 Developmental Procedure/Description of the Plastic and Biomass Torrefaction Machine

The major components of the developed plastic and biomass torrefaction machine (Figure 1) include the bearing, die, screw conveyor, barrel, heating element, hopper, frame, and electric motor. These components are designed to work together efficiently to ensure the proper torrefaction of plastic and biomass materials, transforming them into valuable energy products.

The detailed production drawings for this machine fabrication are contained in the Appendix.

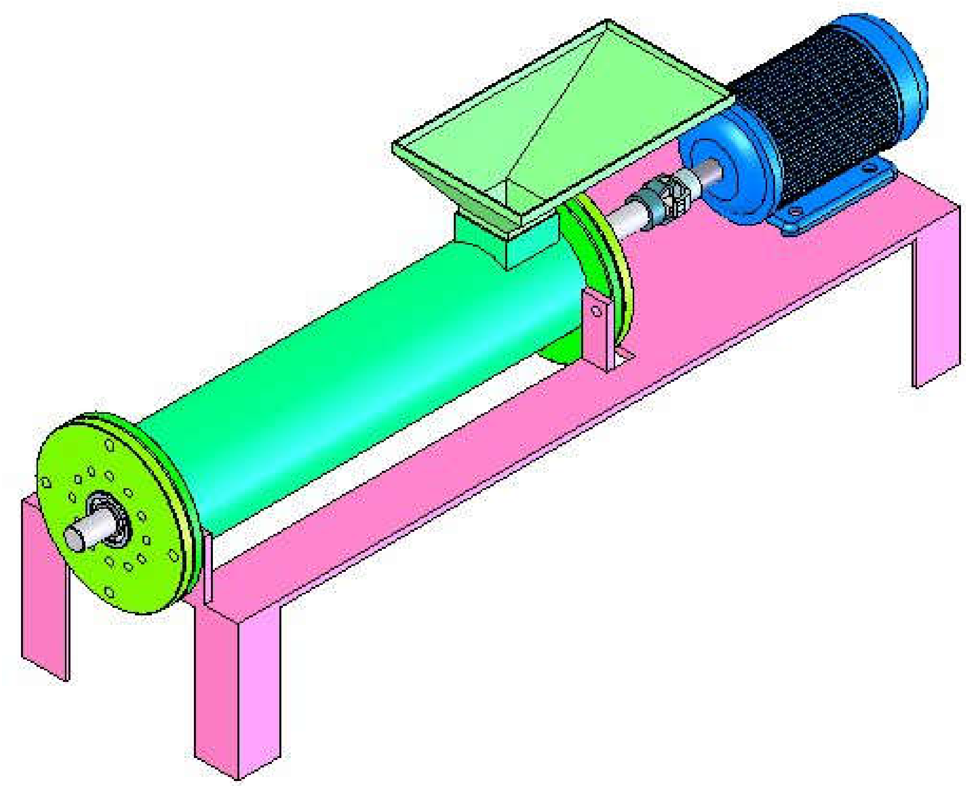

Figure 1: The Isometric Viewof The DevelopedPlastic and Biomass Torrefaction Machine

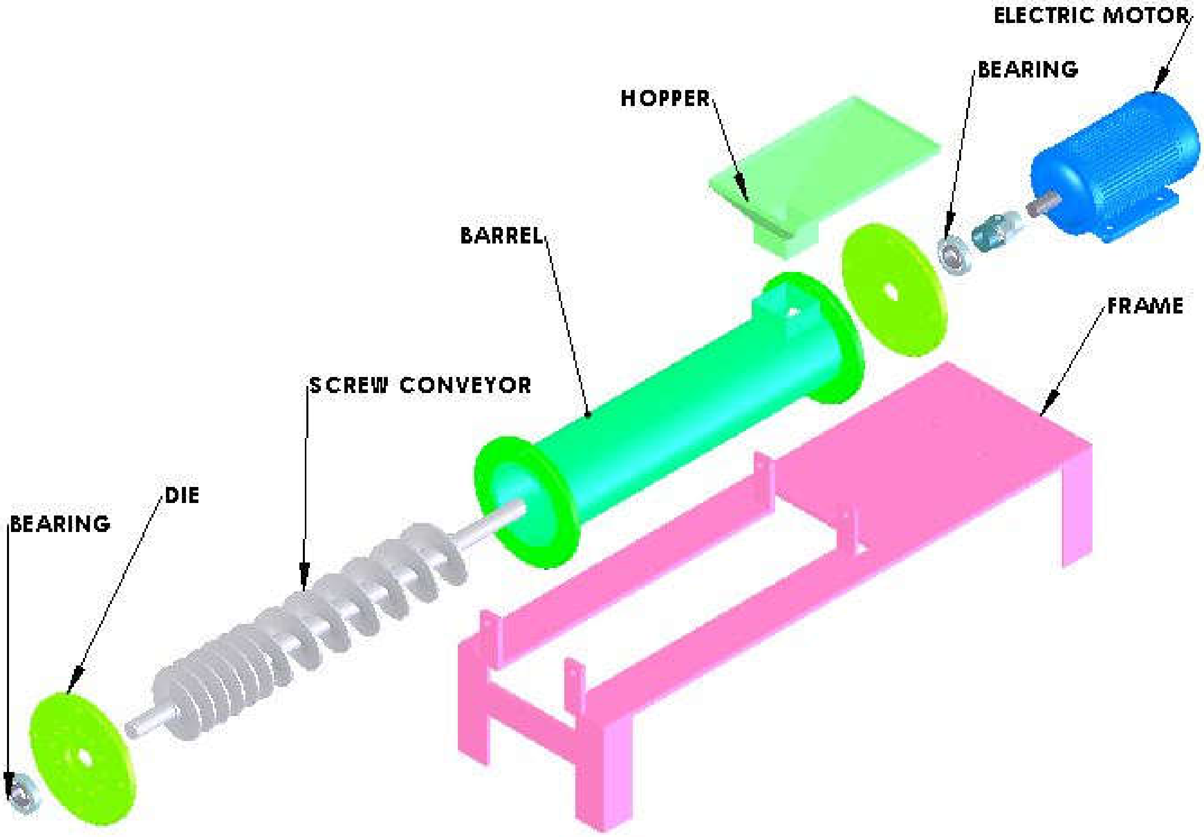

Figure 2: Exploded View of The DevelopedPlastic and Biomass Torrefaction Machine

The components of the torrefaction machine were assembled on a structural frame made from angle iron, which provides rigidity and stability to withstand load vibrations. The core of the machine, the barrel, is constructed from a hollow mild steel pipe chosen for its resistance to high temperatures.

The electric motor, rated at 2HP, drives the shaft of the extruder, enabling the continuous movement of the biomass material through the system. The machine's dimensions were designed to optimize the torrefaction process, ensuring efficient energy conversion. The hopper, fabricated from mild steel sheet, features an entry point for biomass, allowing for easy loading of materials.

At the exit of the barrel, the die is securely installed to shape the torrefied biomass, constructed from gauge 12 mild steel electrode for durability under high-temperature conditions. The bearing assembly, featuring suitable bearings based on load and rotational requirements, supports the smooth operation of the shaft, which is made from mild steel rods.

A screw conveyor, made from mild steel rods, facilitates the transport of biomass through the system, ensuring a continuous flow. Adequate lubrication minimizes friction, and couplings are incorporated for seamless shaft rotation. Functionality tests confirm that the screw conveyor effectively moves the biomass, maintaining the process's efficiency.

The design of the torrefaction machine involved careful selection of materials, including mild steel for its joinability and cost-effectiveness, as well as precise fabrication processes to ensure optimal performance and longevity of the equipment.

3.1 Performance Testing Procedure

The performance evaluation of the torrefaction machine will commence with the activation of the heating element, allowing it to reach the preset temperature as indicated by the thermostat. Once the actual temperature aligns with the desired value, the machine will be powered on.

At this point, the feedstock, consisting of low-density polyethylene (LDPE) and rice husk, will be gradually introduced into the machine through the hopper. The feeding process will occur at a controlled speed ranging from 47 to 50 rpm, while maintaining a temperature of 300°C throughout the torrefaction process.

Monitoring will be conducted to ensure that the temperature remains stable during operation, allowing for optimal conversion of the biomass and plastic waste into high-energy fuel. The results will then be analyzed to determine the efficiency and effectiveness of the torrefaction process under these specified conditions.

3.2 Development of Mathematical Model Procedures for Performance Evaluation of the Torrefaction Extruder Machine

The development of a mathematical model is essential for evaluating the performance of the torrefaction extruder machine. Various properties of the torrefied biomass, including hardness, moisture content, ash content, fixed carbon content, calorific value, volatile matter content, impact strength, and yield strength, are assessed through standardized tests. The data obtained from these tests, conducted using a Universal Testing Machine (UTM) and other equipment, are vital for understanding the machine's efficiency and the quality of the torrefied biomass.

Hardness Test (ASTM D2240)

The hardness of the torrefied biomass was measured in accordance with ASTM D2240 standards, using the UTM. Hardness values were calculated based on the material's resistance to indentation, applying the formula:

$$H = \frac{F}{A} \tag{18}$$

Where:

H = Hardness

F = Applied force (N), as measured by the UTM

A = Area of indentation (mm^2)

Moisture Content (ASTM D4442)

Moisture content was determined by measuring the weight loss of the biomass after drying it in a controlled environment. The UTM was utilized to record both the initial and final weights of the sample. Moisture content was calculated using the following formula:

$$M_C = \frac{W_i - W_f}{W_i} \times 100 \qquad (19)$$

Where:

M_C = Moisture content (%)

W_i = Initial weight of the sample (g), recorded by the UTM

W_f = Final weight after drying (g)

Ash Content

Ash content, representing the inorganic residue left after combustion, was determined following combustion tests. Values were obtained from the UTM, and the formula used for ash content is:

$$A_C = \frac{W_{ash}}{W_s} \times 100 \qquad (20)$$

Where:

A_C = Ash content (%)

W_{ash} = Weight of ash (g), measured post-combustion

W_s = Weight of the sample before combustion (g)

Fixed Carbon Content

Fixed carbon content, which indicates the amount of carbon available for combustion, is derived from the moisture, volatile matter, and ash content. The necessary data for fixed carbon calculations were provided by the UTM, as follows:

$$F_C = 100 - (M_C + V_M + A_C) \qquad (21)$$

Where:

F_C = Fixed carbon content (%)

M_C = Moisture content (%)

V_M = Volatile matter content (%)

A_C = Ash content (%)

3.2.5 Calorific Value

The calorific value, which measures the energy output during combustion, was calculated using data from the UTM. The heat energy produced during combustion was assessed, leading to the determination of calorific value using the formula:

$$C_V = \frac{Q}{Ws} \tag{22}$$

Where:

C_V = Calorific value (MJ/kg)

Q = Heat energy produced (J), obtained through combustion tests

Ws = Weight of the sample (kg)

Volatile Matter Content

Volatile matter content was evaluated by measuring the weight loss of the sample when heated to a specified temperature. The UTM recorded the initial and final weights, allowing the volatile matter content to be calculated as follows:

$$V_M = \frac{W_i - W_f}{W_i} \times 100 \tag{23}$$

Where:

V_M = Volatile matter content (%)

W_i = Initial weight of the sample (g), recorded by the UTM

W_f = Final weight after heating (g)

Impact Test (ASTM D256)

Impact strength was measured according to ASTM D256 standards, using the UTM to determine the energy absorbed by the biomass during impact. Impact energy was calculated with the following formula:

$$I_E = \frac{W \times h}{A} \tag{24}$$

Where:

I_E = Impact energy (J/m²)

W = Weight of the hammer (N), utilized in the UTM

h = Height of the drop (m)

A = Area of the sample (m²)

Yield Strength

Yield strength of the biomass was measured using the UTM, indicating the stress at which the material begins to deform plastically. Yield strength was calculated using the formula:

$$Y_S = \frac{F_y}{A} \tag{25}$$

Where:

Y_S = Yield strength (Pa)

F_y = Force at the yield point (N), measured by the UTM

A = Cross-sectional area of the sample (m^2)

4.0 Results and Discussion

The performance test results for the plastic and biomass torrefaction machine are presented in Table 1. These values were obtained using the Universal Testing Machine (UTM) under controlled experimental conditions. The results reveal important insights into the physical and chemical properties of the torrefied materials, such as moisture content, calorific value, ash content, volatile matter content, and fixed carbon content. These parameters are critical to assessing the efficiency of the torrefaction process, the quality of the final product, and the machine's operational capabilities.

Table 1: Results of the Performance Test of Plastic and Biomass Torrefaction Machine

Temperature (°C)	**Moisture Content (%)**	**Hardness (Shore D)**	**Impact Test (J/m^2)**	**Yield Strength (MPa)**	**Ash Content (%)**	**Volatile Matter Content (%)**	**Fixed Carbon Content (%)**	**Calorific Value (kJ/kg)**
300	0.3900	60.0000	0.0109	6.5872	7.6190	0.0200	91.1200	8337.3500
295	0.4000	58.5000	0.0112	6.5500	7.5000	0.0220	90.9000	8320.0000

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290	0.4050	57.8000	0.0115	6.5000	7.7000	0.0230	90.8000	8295.5000
280	0.4200	59.2000	0.0120	6.6000	7.5500	0.0210	91.0000	8305.2000
270	0.4300	59.5000	0.0118	6.5600	7.6500	0.0195	90.9500	8310.8000

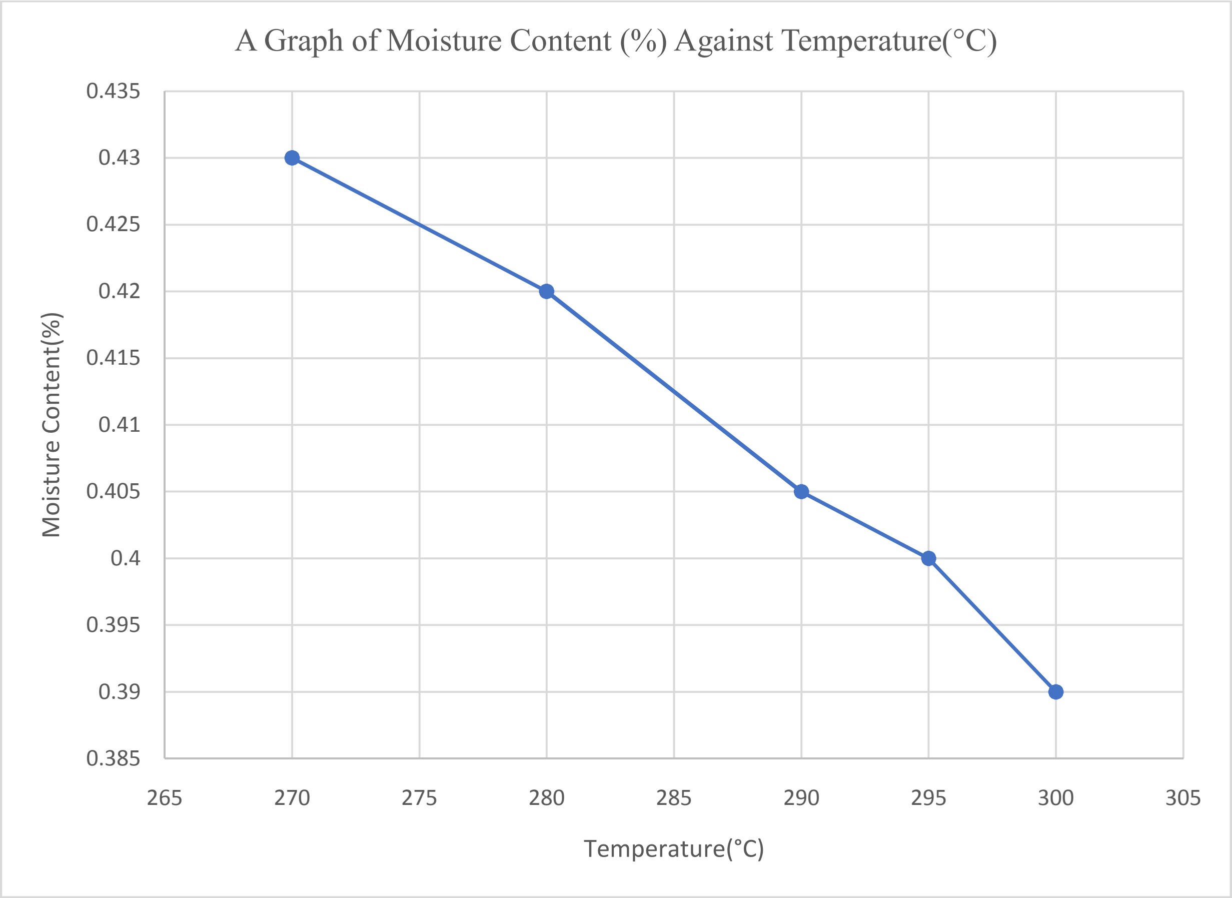

Figure 3:Interval plot ofmoisture content versus temperature

Figure3 shows various moisture content for different temperature intervals. The temperature at 270-, 280-, 290-, 295- and 300-degreeCelsiusrespectively.Figure 3 illustrates a decline in moisture content as the temperature increases from 270°C to 300°C. This decrease in moisture content highlights the efficiency of the torrefaction process in removing bound water from the raw materials. At higher temperatures, the heat input is more effective at breaking down the molecular structure of the biomass and plastic, leading to a greater reduction in moisture.

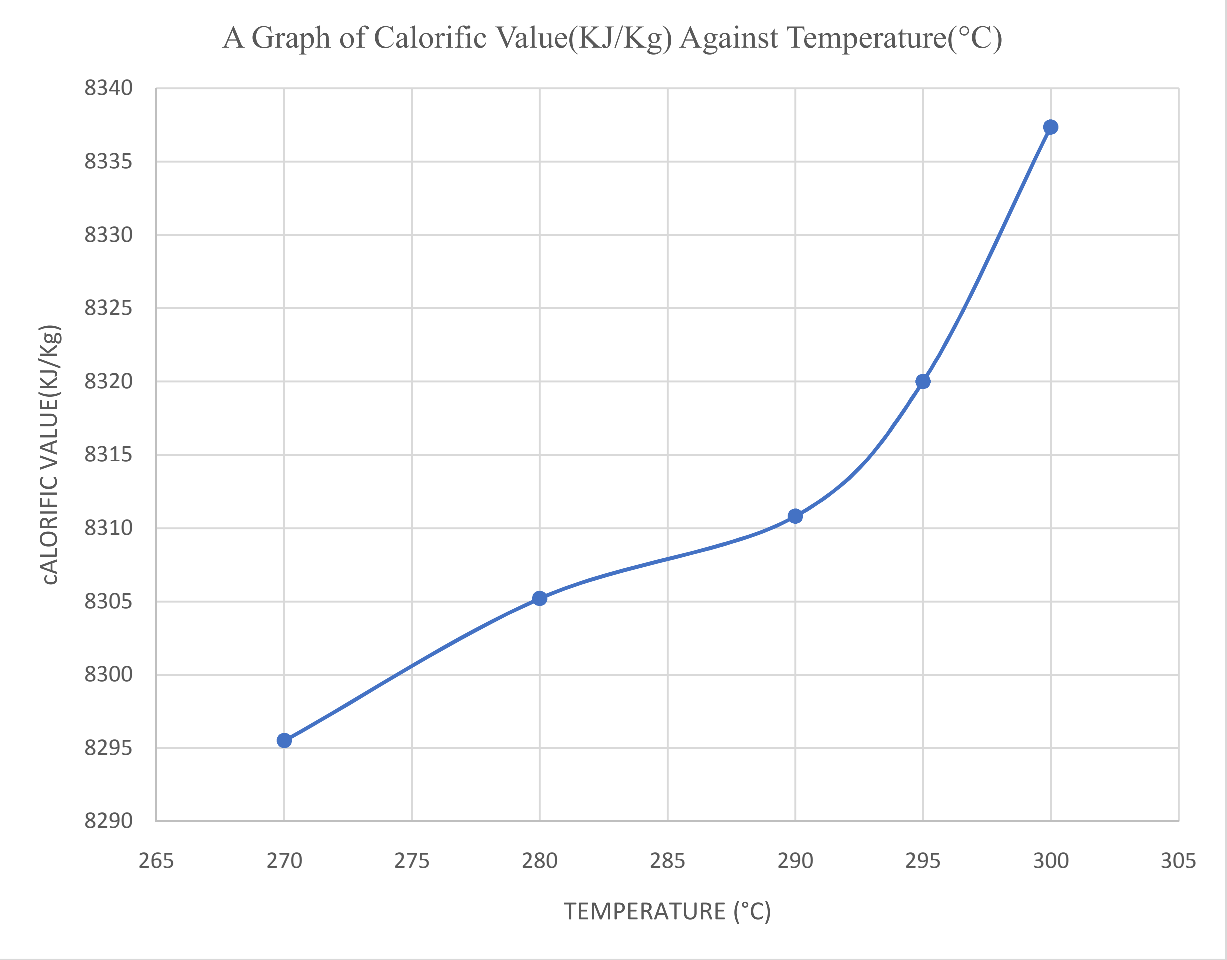

Figure 4:Interval plot of calorific value versus temperature

Figure4 illustrates the calorific value at various temperatures, specifically at 270°C, 280°C, 290°C, 295°C, and 300°C. From the graph, it is evident that the temperature at 300°C yields the lowest moisture content and the highest calorific value. This observation indicates that as the temperature increases, the torrefaction process becomes more efficient in removing moisture and enhancing the energy density of the product.

5.0 Conclusion and Recommendation

The plastic and biomass torrefaction machine was designed, developed, and its performance evaluated at Enugu State University of Science and Technology, Enugu. The machine effectively processes plastic and biomass feedstocks by converting them into high-quality torrefied products with enhanced calorific value and reduced moisture content. The results showed that increasing temperature during the torrefaction process significantly improved the energy density and stability of the final product, making it suitable for energy generation applications. The machine’s ability to remove moisture and increase fixed carbon content demonstrates its efficiency in carbonization, providing a more durable and energy-dense material.

It is recommended that this torrefaction machine be adopted for large-scale waste management and energy production, particularly for plastic and biomass waste. The machine's design could be further optimized to accommodate varying feedstock types and operational conditions, ensuring maximum efficiency. Additionally, the machine offers an environmentally friendly solution by converting plastic waste into a valuable resource, thereby contributing to sustainable waste management practices.

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