Development of a Free-Fall Pyrolysis Reactor for Biofuel Production Using Sugarcane Bagasse and Cassava Rhizomes as Feedstocks

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Abstract

This study presents the design, fabrication, and evaluation of a free-fall reactor with a capacity of 1 kg/hr for biofuel production from sugarcane bagasse (SCB) and cassava rhizome (CR). The reactor was designed based on particle heating rate and free-fall velocity principles, with a heating rate of 50°C/min. Experiments were conducted using various blends of SCB and CR at temperatures ranging from 400°C to 650°C, with a residence time of 30 minutes. The results showed that a 50:50 blend of SCB and CR yielded the highest bio-oil yield of 36.2%, with a corresponding heating value of 23.6 MJ/kg. At an operating temperature of 550°C, the yields of biochar and biogas were 16.2% and 47.6%, respectively. This study demonstrates the feasibility and sustainability of utilizing agricultural residues for bioenergy production through free-fall pyrolysis, offering a promising solution to the energy crisis in developing nations.

Keywords: *Free-fall reactor, sugarcane bagasse, cassava rhizome, pyrolysis, biofuel.*

1.0 Introduction

The escalating cost of fossil fuels and the steady decline of petroleum reserves, largely driven by population growth, have recently intensified the need for sustainable energy alternatives. Biomass has emerged as one of the most promising renewable energy sources to tackle these challenges. It can significantly cut down on pollution resulting from fossil fuel usage, particularly the release of gases such as carbon dioxide, sulphur oxides, and nitrogen oxides [1]. Essentially, biomass consists of organic substances primarily made up of carbon, hydrogen, and oxygen, with trace amounts of nitrogen and sulphur [2]. Biomass encompasses a diverse array of both natural and processed substances, including materials like cassava rhizomes and sugarcane bagasse. The latter is a fibrous by-product left after extracting juice from sugarcane stalks. The richness in cellulose, hemicellulose, and lignin makes sugarcane bagasse serves as a valuable resource for bioenergy production and the synthesis of bio-based chemicals [3]. Additionally, it is widely used for thermal and electrical energy in sugar processing plants, as well as in paper manufacturing, livestock feed, and the creation of eco-friendly disposable packaging [4]. Nigeria heavily cultivates cassava, which serves as both a staple crop and a key economic resource. With an estimated production of 63 million tons in 2021, the country was among the world's top cassava producers. The non-edible parts of the plant (such as rhizomes, stalks, peels, and leaves) are often discarded as residues [5]. These cassava by-products are low-cost, sustainable, and widely accessible feedstocks that can be utilized for biofuel production due to their high hydrocarbon content [6]. Unfortunately, they are mostly burned in the fields, wasting their energy potential. Pyrolysis, a method of heating biomass without oxygen at 300°C to 700°C, can transform cassava rhizomes into valuable outputs like biochar, bio-oil, and biogas [7].

A range of reactor designs is utilized in biomass pyrolysis, each differing in structure and mode of operation. Frequently applied types include fixed-bed, fluidized-bed, vacuum, ablative, solar-driven, plasma, microwave-based, and free-fall reactors. The operating temperature of these systems typically spans from 250 °C to 600 °C, influenced by the nature of the biomass and the desired proportions of solid, liquid, and gas products. Pyrolysis converts biomass into bio-oil, biochar, and biogas [8], [9], [10], [11], [12]. Product yields in pyrolysis are influenced by operational parameters such as temperature, heating rate, and residence time. This thermal decomposition process typically occurs under atmospheric or mildly elevated pressures and is categorized into slow, moderate, fast, ultra-fast, or flash types, depending on variations in those factors and the resulting products [13].

Struhs et al. [14] explored the integration of fast and slow pyrolysis methods to transform various biomass materials (including hybrid poplar, maple, pine, and sugarcane bagasse) into biochar and bio-oil. Their approach involved a combination of a free-fall and batch reactor to enhance the efficiency and quality of the outputs. In another study, Promsampao et al. [11] used a fluidized-bed reactor for fast pyrolysis of palm kernel cake, focusing

on identifying process parameters that yield optimal bio-oil properties. Meanwhile, Sirijanusorn et al. [15] employed a counter-rotating twin screw reactor to pyrolyze cassava rhizomes, examining factors such as temperature, particle size, and nitrogen flow rate. They concluded that 550°C was the most effective temperature for maximizing bio-oil production. Pattiya et al. [8] employed a laboratory-scale free-fall reactor to conduct pyrolysis on agricultural waste derived from sugarcane and cassava. Their research examined how different types of biomass and pyrolysis conditions influenced the distribution and properties of the resulting products. Singh et al. [16] carried out pyrolysis of torrefied Acacia nilotica using a fixed-bed tubular reactor under a nitrogen environment. They applied a central composite design along with a response surface methodology to optimize the process and enhance bio-oil yield. Similarly, Rueangsan et al. [17] explored the effects of catalyzed fast pyrolysis of cassava rhizomes in a free-fall reactor, using soil conditioners as catalysts. Their results showed an increase in char yield, while bio-oil and gas outputs declined.

2.0 Materials and Methods

Sugarcane bagasse used was collected from a farm located along Bacita Sugar Company in Kwara State, Nigeria. The collected sugarcane bagasse was first dried and ground to a particle size of 0.5 mm to ensure consistency in the samples. The SGB was then stored in a dry place before being used in the pyrolysis experiments. Cassava rhizome was obtained from TJ International Farm located in Konta Ijabe in Osun state, Nigeria. The samples were washed, peeled, and sliced into small pieces. Subsequently, a drying process was undergone and ground to 0.5 mm particle sizes. The proximate and ultimate analyses of the raw cassava rhizome and sugarcane bagasse feedstocks (Table 1) were conducted in accordance with ASTM D3176 and ASTM D3172, respectively.

Table 1. The proximate and ultimate analyses of the biomass feedstocks on a dry basis

Analysis	% wt	Cassava rhizome	Sugarcane bagasse
Proximate	Moisture	7.92	5.91
	Fixed carbon	13.15	11.45
	Ash	6.37	5.55
	Volatile matter	72.56	77.09
	LHV (MJ/kg)	12.5	18.2
Ultimate	Carbon	48.01	46.75
	Hydrogen	6.4	6.6
	Nitrogen	0.97	0.56
	Oxygen	44.62	46.09

2.1 Design principle

The design of the reactor considers key principles such as the design particle heating rate and the particle's free-fall velocity. The heating rate, indicating how fast the biomass particles are heated during their descent through the reactor, is a crucial parameter influencing the bio-oil quality. If the heating rate is too low, incomplete pyrolysis might occur, leading to low bio-oil yields. Conversely, if the heating rate is excessively high, thermal cracking and undesirable reactions could compromise the bio-oil quality. Simultaneously, the free-fall velocity of the particles significantly impacts the residence time within the reactor. The duration that biomass particles spend in the reactor is pivotal for bio-oil yield and quality. If the free-fall velocity is too high, inadequate residence time might prevent complete pyrolysis, reducing bio-oil yields. Conversely, if the velocity is too low, prolonged exposure to high temperatures may degrade the biomass, resulting in inferior bio-oil quality. Balancing these parameters is fundamental for optimizing the design and performance of the free-fall reactor.

2.1.1 Particle heating rate

The optimal temperature range for fast pyrolysis falls between 450°C and 550°C. Assuming complete pyrolysis occurs when the center of a spherical biomass particle reaches 500°C, the time needed for this temperature attainment should be calculated using the lumped capacitance method. This method assumes a uniform temperature within the particle and is applicable when the ratio of surface convection to internal conduction, represented by the Biot number, is small [19]. Biot number is given by:

$$Bi = \frac{hL_c}{k} \tag{1}$$

where h is the convective heat transfer coefficient at the surface of the body, and k is the conductive heat transfer coefficient within the body. L_c is the characteristic length, and it is the ratio of the volume to the surface area of the object.

$$L_c = \frac{V}{A_s} \tag{2}$$

The lumped capacitance method is used when $Bi \leq 0.1$. To obtain the Biot number, the conductive and convective heat transfer coefficient and the particle diameter must be determined. Since the particle would be falling freely into the reactor, only the convective and radiative heat transfer is significant. Radiative heat transfer serves as the predominant method through which heat is transferred within an entrained flow reactor [19]. The radiative heat transfer coefficient was obtained from the expression (Equation 3).

$$h_{rad} = \frac{\ddot{I}f\left(T_p{}^2 + T^2{}_{wall}\right)\left(T_p + T_{wall}\right)}{\frac{1}{\hat{I}\mu_p} - 1 + \frac{1}{F_{12}}} \tag{3}$$

where σ is the Stephan Boltzmann constant, T_p is the temperature of the particle, T_{wall} is the temperature of the reactor wall, ε_p is the emissivity of the particle, and F_{12} is the view factor from the particle to the reactor wall. h_{rad} was calculated by taking the temperature of the particle to be 25°C, the temperature of the wall is taken to be 650°C, the emissivity and view factor are assumed to be 1 and 0.7, respectively. Once more, presuming that complete pyrolysis takes place when the particle reaches a temperature of 500°C, the time required to reach this temperature can be calculated from the relation (Equation 4).

$$\frac{T - T_{\hat{a}\hat{z}}}{T_i\hat{A} - \hat{A}T_{\hat{a}\hat{z}}} = \hat{A}e^{-bt}\hat{A}\hat{A} \tag{1}$$

where T_∞ is the temperature of the fluid, which is equal to the wall temperature, T_i is the initial temperature of the particle, which is 25°C, and b is the time constant. T is the desired temperature of the particle, which was assumed to be 500°C. The time constant b is given in Equation (5).

$$b = \frac{hA_s}{\rho V C_p} \tag{2}$$

Replacing h with h_{rad}, with the density specific heat and diameter of the biomass being specified, the time constant can be obtained. Assuming a particle of 1mm diameter, the density of sugarcane bagasse is $120\frac{Kg}{m^3}$, and the specific heat of most biomass is reported to be $2.27\frac{KJ}{KgK}$ [20]. The time taken for the biomass particle to get to 500°C can be obtained.

2.1.2 Particle free-fall velocity

Knowing that the vapour residence time for fast pyrolysis is 2 seconds or less. The required length of the reactor can be determined from the terminal setting velocity of the biomass particle and the already obtained time. The velocity of the biomass particle can be obtained from the relation (Equation 6).

$$u_t = \sqrt{\frac{4.g.2r_o.(\rho_p - \rho_f)}{3\rho_f C_D}} \tag{6}$$

where u_t is the particle setting velocity, r_o is the stoke radius, g is gravity, ρ_p is the density of the particle, ρ_f is the density of the fluid, and C_D is the coefficient of drag. The particle free-fall velocity was obtained using a simple program. Therefore, the minimal reactor length necessary to heat a 1mm sugarcane bagasse particle to 500°C is computed using Equation 7.

$$L = u_t\tilde{A} - t \tag{3}$$

2.1.3 Heating of the reactor

The reactor needs to be heated to elevate the biomass temperature to the desired level. Heat transfer occurs through three modes: conduction, convection, and radiation. Conduction involves heat transfer between two bodies in direct contact without the bulk movement of the bodies. Convection, on the other hand, happens through currents of moving fluid and is mainly observed in fluids. Radiation is a heat transfer mode where heat waves are emitted to the body. In the scenario where particles fall freely into the reactor, radiation is the primary mode of heat transfer. It takes place between the reactor wall and the biomass particles. The heat needed to vaporize the biomass and elevate the carrier gas to a temperature of 500°Cis calculated using the expression in Equation 8.

$$\dot{Q} = \dot{m}L \tag{4}$$

where $\dot{m}$ is the mass flow rate of the biomass, while L is the latent heat of vaporization of the biomass. Assuming a biomass flow rate of 1kg/hr, the amount of heat required can be obtained from Equation 8.

2.1.4 Insulation of the reactor

To minimize heat loss through the reactor wall, fiberglass insulation was chosen and wrapped tightly around the reactor to minimize air gaps and ensure complete coverage. The thickness of the insulation layer was determined based on the desired level of heat loss reduction and the operating temperature of the reactor. The insulation unit was modeled using the heat transfer equation:

$$Q = \frac{kA(T_h - T_c)}{L} \tag{9}$$

where, Q is the rate of heat transfer through the insulation, k is the thermal conductivity of the insulation material, A is the surface area of the reactor, Th is the temperature of the hot surface (inside the reactor), Tc is the temperature of the cold surface (outside the insulation), and L is the thickness of the insulation layer.

2.1.5 Design of cyclone

Cyclones, also known as cyclone separators, are devices that utilize the principle of inertia to eliminate particulate matter from fuel gases. There are two primary designs: Gas cyclones, used for removing entrained particles from gas streams, and hydro cyclones, employed to separate fluids of varying densities. This study specifically utilized the gas cyclone separator, focusing on separating char from vapor emerging from the cyclone.

2.1.6 Calculation of the produced amount of char

The quantity of char produced can be extrapolated by assuming that 0.25 of the biomass feed will be turned into char, which has a bulk density of $400 \frac{kg}{m^3}$ [20]. The volume of char produced was estimated from Equation 10.

$$volume\ of\ char\ produced = \frac{0.25 × biomass\ feed\ rate}{density\ of\ char} \tag{50}$$

2.1.7 Calculation of cyclone size

A factor of 2 was used to design the cyclone to prevent the cyclone from filling up to the top. The standard 2D cyclone dimension was employed in this design. The standard 2D cyclone is shown in Figure 1.
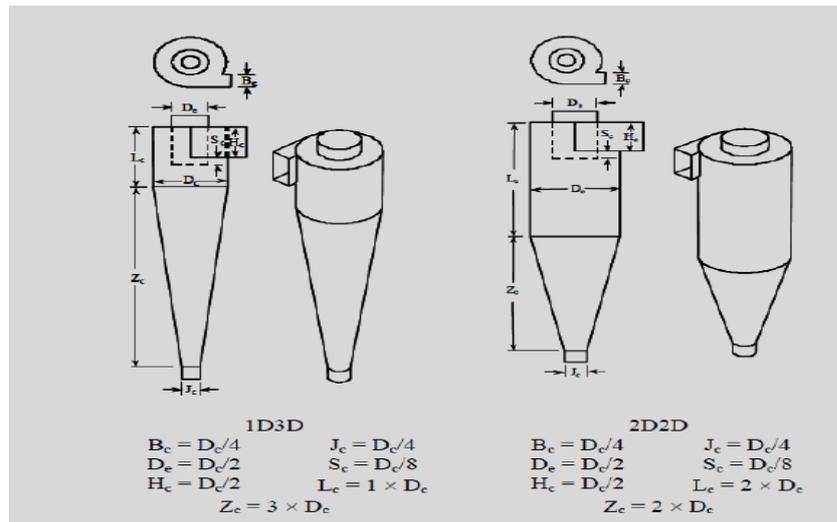
Figure 1: A 2D cyclone

From the above diagram, the volume (V) of the cyclone is obtained to be

$$V = \frac{\pi D_c^2}{4} \times 2D_c + \frac{1}{3} \times \pi \times 4D_c^2 \times 2D_c \tag{11}$$

Relating Equation 11 to the volume of the cyclone, the diameter of the cyclone Type equation here. was obtained.

2.1.8 Thermal Conversion Efficiency of Pyrolysis Reactor

Thermal conversion efficiency (TCE) in pyrolysis quantifies the effectiveness of converting the chemical energy stored in biomass into useful pyrolysis products, namely biochar, bio-oil, and biogas yield. TCE is calculated as the ratio of the total energy content of the pyrolysis products to the energy content of the original biomass feedstock. It is expressed as

$$\sum \{ \frac{m_i \times CV_i}{m_{biomass} \times CV_{biomass}} \} \times 100 \tag{12}$$

where m_i, CV_i represent the mass and calorific value of each product (biochar, bio-oil, biogas), respectively. This metric provides insights into energy retention and distribution across pyrolysis products.

2.1.9 Condensing Unit and Oil Collector

The fundamental design of the condensing unit involves cooling the vapor stream to a temperature where the bio-oil can condense and be gathered. Typically, this unit comprises a heat exchanger, a condenser, and a collection tank. The heat exchanger cools the vapor stream before it enters the condenser, which is meticulously engineered to provide a large surface area for efficient bio-oil condensation. The condensed bio-oil is then stored in the collection tank for further use. The oil collector is a container where the bio-oil is collected from the unit. The collection bottle glass was chosen to accommodate the expected volume of bio-oil produced. The bottle was made of glass, and the exit pipe was connected to a panel to sense gases such as CO_2, O_2, and CH_4. The detailed drawings for the free-fall reactor are shown in Figure 2.
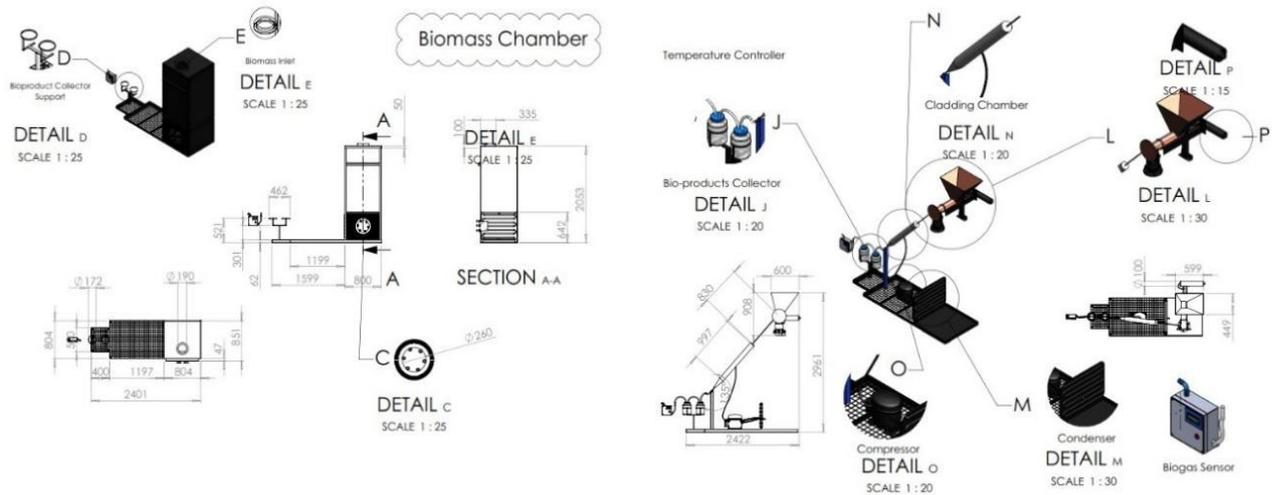
Figure 2: The detailed fabrication drawings for the free-fall reactor

2.2 Experimental setup and operational procedures

The conversion of biomass feedstocks into biochar, bio-oil, and biogas was achieved via thermochemical processes in the developed free-fall pyrolytic reactor. The reactor temperatures were varied from 450°C to 600°C, incrementing by 50°C in successive experimental runs. Throughout the tests, nitrogen gas was introduced at a uniform flow rate of 7 g/min [4]. Twenty experimental trials were conducted to study the pyrolysis behaviour of SCB and CR and to assess the yields of bio-oil, char, and gases produced. The process took place inside a reactor heated between 450°C and 600°C for 30 minutes, generating vapors and solid residues. These vapors were quickly cooled and condensed using a condenser maintained at about 5°C by an external chilling system, allowing the bio-oil to be collected in a vessel. Additionally, sensors for detecting CH4, CO, and O_2 gases were installed at the outlet of the system. The biochar and bio-oil underwent proximate analysis according to the ASTM E1755-01 guideline. A Leco TruSpec Micro CHNS analyzer was employed to measure the elemental composition, including carbon, hydrogen, nitrogen, and sulfur. Oxygen content was inferred using alternative estimation techniques, and the higher heating value was assessed with an oxygen bomb calorimeter.

3.0 Results and Discussion
3.1 Design Result and Parameters

The design parameters and specifications were obtained from the already established equations (1-11). Table 2 presents dimensions of each component to optimize the pyrolysis process, ensuring efficient biomass conversion and maximum biofuel yield. Figure 3 shows the developed free-fall reactor.

Table 2: Dimensions of each component of the pyrolysis unit

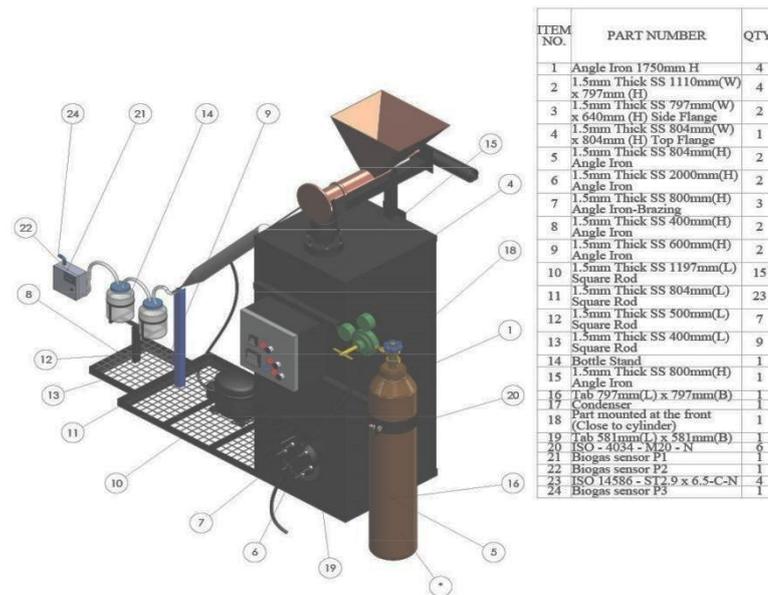| S/N	Component	Diameter (mm)	Length (mm)	Breadth (mm)	Height (mm)
1	Auger	25	500	-	-
2	Hopper	-	200	200	150
3	Reactor	250	-	-	1200
4	Combustion chamber	-	500	500	1300
5	Cyclone	100	-	-	300

Figure 3: Developed free-fall reactor

Table 3 outlines the blending ratios of sugarcane bagasse and cassava rhizomes, along with the temperatures applied in the reactor. The experimental results, along with the types of biofuels generated for each Run, are summarized in Table 3. Run 11 produced a peak bio-oil yield of 36.2%. At a temperature of 550 °C, the yields for biochar and biogas were 16.2% and 47.6%, respectively. These findings suggest that an equal blend of SCB and CR is optimal for bio-oil generation under these conditions.

Table 2. Experimental data and the product's yields.

Run	SCB (%)	CR (%)	Temperature (°C)	Biochar (BC) yield (%)	Bio-oil (BO) yield (%)	Biogas (BG) yield (%)
1	100	0	450	25.1	28.2	46.7
2	100	0	500	22.2	34.4	43.4
3	100	0	550	18.6	28.7	52.7
4	100	0	600	16.7	23.5	59.8
5	75	25	450	22.6	31.2	46.2
6	75	25	500	20.3	31.2	48.5
7	75	25	550	17.6	33.3	49.1
8	75	25	600	16.2	26.7	57.1
9	50	50	450	20.1	32.8	47.1
10	50	50	500	18.7	35.3	46
11	50	50	550	16.2	36.2	47.6
12	50	50	600	14.4	34.3	51.3
13	25	75	450	20.6	27.4	52
14	25	75	500	17.1	29.9	53
15	25	75	550	15.9	29.9	54.2
16	25	75	600	15.2	32.1	52.7
17	0	100	450	15.2	34.2	50.6
18	0	100	500	15.1	35.7	49.2
19	0	100	550	14.5	34.8	50.7
20	0	100	600	13.7	33.7	52.6

Figure 4 presents the proximate and ultimate analyses of biochar and bio-oils derived from both individual base feedstocks and a combined 50:50 feedstock ratio, which showed higher bio-oil yields. The elemental analysis

of the resulting bio-oils aligns with earlier findings by Pattiya et al. [8] and Struhs et al. [14], particularly in terms of carbon (53–65%), hydrogen (3.9–6.5%), nitrogen (0.4–0.8%), and oxygen (32–38%) contents. According to Pattiya et al. [8], Struhs et al. [14] and Singh et al [16], and de Almeida et al. [21], biochar typically contains 45–65% carbon, 2–7% hydrogen, 0.3–2.0% nitrogen, and 4–35% oxygen, which corresponds closely with the composition observed in this research. The oxygen-to-carbon and hydrogen-to-carbon ratios of the bio-oil were similarly in the expected ranges of 0.5–0.7 and 0.06–0.2, respectively. Among the various samples, the bio-oil derived from an even (50:50) feedstock blend exhibited the lowest O/C ratio and the highest energy content, measuring 23.6 MJ/kg. The decrease in the oxygen-to-carbon ratio reflects a diminished oxygen presence, which boosts the bio-oil's energy output [14]. Nonetheless, refining techniques such as hydrodeoxygenation and catalytic cracking are essential to upgrade the bio-oil for compatibility with conventional fuel engines.
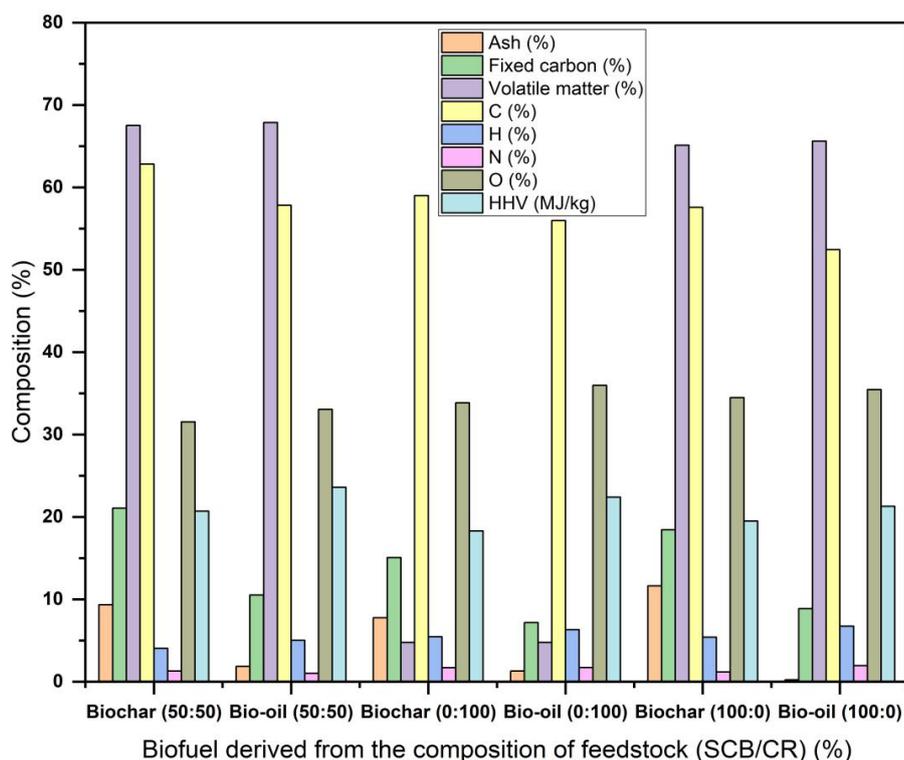

Figure 4: proximate and ultimate analyses of biochar and bio-oils derived from both individual base feedstocks and a combined 50:50 feedstock ratio

3.2 Influence of the reactor's temperature on the quantities of products obtained

Pyrolysis reactor temperature is a key factor that shapes the yield distribution of biochar, bio-oil, and biogas. The study varied this parameter across experiments to evaluate its influence and to identify the temperature range that maximizes bio-oil yield. Figure 4 illustrates how yield outputs change with temperature across biomass types. As shown in Figure 5(a), the use of 100% SCB as feedstock reveals a non-linear response of bio-oil yield to increasing pyrolysis temperatures. Initially, the yield is modest at lower temperatures but improves as the temperature climbs, peaking between 450 °C and 550 °C. Above this range, a decline in bio-oil yield occurs, attributed to secondary reactions that lead to more char and gas formation [4]. Additionally, there appears to be a significant connection between reactor temperature and the quantity of biochar produced. A temperature rise corresponded with a decline in char formation, due to the greater thermal breakdown of SCB materials. In contrast, biogas output increased progressively, driven by the improved conversion of SCB components under higher heat conditions.

Figure 5(b) illustrates the influence of temperature on bio-oil yield when using a feedstock composed of 75% SCB and 25% CR. The pattern is like that in Figure 5(a), showing an increase in bio-oil yield as the temperature goes up. The presence of cassava rhizome likely contributes to a higher bio-oil yield compared to using 100% SCB. Increased temperatures cause thermal decomposition in both SCB and CR, leading to less char formation. Biogas production also rises steadily with higher reactor temperatures. Figure 5(c) shows the temperature effect on bio-oil yield for an equal mixture of 50% SCB and 50% CR. Bio-oil yield peaks at 36.2% at 550 °C during pyrolysis, following previous trends. Biochar decreases between 450 and 600 °C due to organic matter breakdown, while biogas rises from secondary cracking of char and vapours [22]. Figure 5(d) shows that with a 25% SCB and 75% CR blend, bio-oil yield increases up to 600 °C as biochar declines, indicating cassava rhizome's composition strongly influences char formation even at lower temperatures.

As the reactor temperature increased, biogas production also rose until it plateaued at a maximum stable level. For feedstock composed entirely of cassava rhizome (CR) without sugarcane bagasse (SCB), char yield decreased while biogas output increased with temperature (see Figure 5(e)). This is likely due to the unique chemical makeup of cassava rhizome, which undergoes varying thermal breakdown processes affecting char generation. Additionally, co-pyrolyzing sugarcane bagasse and cassava rhizomes resulted in greater bio-oil production than when either was pyrolyzed alone. The 50:50 feedstock mix showed a lower oxygen-to-carbon ratio, indicating a higher energy density in the bio-oil. These results suggest that combining SCB and CR enhances biofuel yield and quality through synergistic interactions.
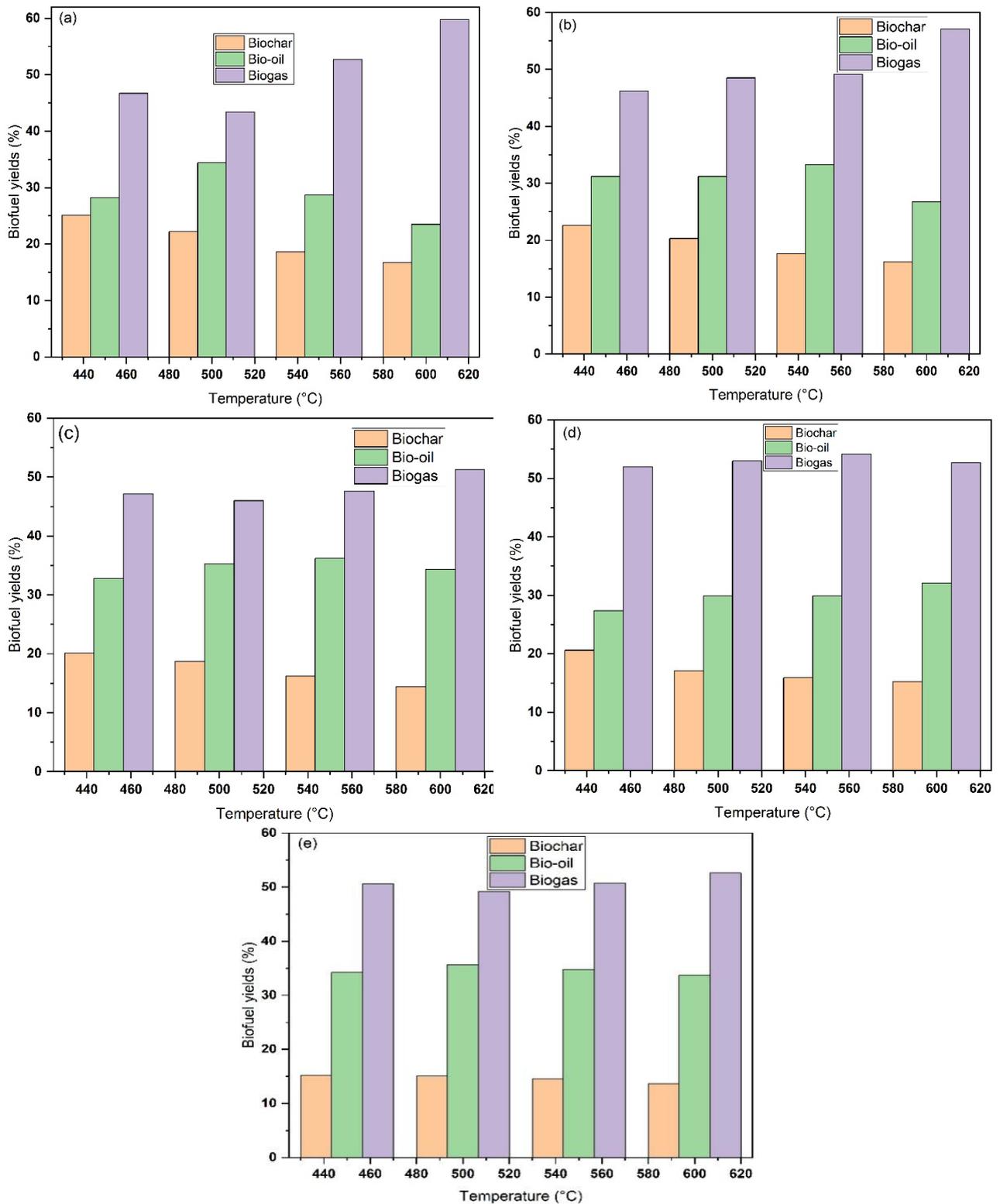

Figure 5. Variations in temperature and their influence on biochar, bio-oil, and biogas outputs for sugarcane bagasse (SCB) and cassava rhizome (CR) at blend ratios of (a) 100:0, (b) 75:25, (c) 50:50, (d) 25:75, and (e) 0:100

3.3 Compositions of biogas

The influence of changes in biomass composition on the proportion of biogas generated during pyrolysis was relatively small. Biogas yields remained largely consistent across the various mixtures, implying that other factors, such as temperature and heating rate of the reactor, have a more significant impact on gas production [23]. The combination of sugarcane bagasse and cassava rhizome in the feedstock enhances the diversity of the resulting gas composition. Due to the different chemical profiles of these two biomasses, pyrolysis produces several gases, including carbon monoxide, carbon dioxide, methane, and volatile organic compounds. Lower temperatures cause incomplete volatilization, leading to reduced biogas yields [6]. For SCB:CR ratios of 100:0, 50:50, and 0:100, the oxygen concentrations were 4.88 ppm, 3.99 ppm, and 14.03 ppm, respectively. Increased methane levels, as illustrated in Table 4, are attributed to lignin's thermal breakdown and subsequent tar cracking [24]. The equal mix of SCB and CR produced the highest methane and lowest carbon dioxide levels, suggesting better fuel suitability [25]. The generated biogas, particularly with elevated methane content, is suitable for use in household cooking, industrial heating, electricity generation, and as a supplementary fuel in combined heat and power (CHP) systems [4].

Table 4. Compositions of biogas for SCB and CR feedstocks at different proportions.

Proportion of SCB and CR	CO_2 (ppm)	O_2 (ppm)	CH_4 (ppm)
100:0	16.75	4.88	33.92
50:50	11.87	3.39	42.19
0:100	17.81	4.03	34.77

4.0 Conclusions

This study provides a comprehensive design framework to support future research on the production of bio-oils from agricultural biomass using a free-fall pyrolytic unit. Additionally, it examines the influence of pyrolysis temperature—ranging from 450°C to 700°C—on the yield distribution of products derived from sugarcane bagasse and cassava rhizome. The highest bio-oil yield, recorded at 36.2% with a heating value of 23.6 MJ/kg, was obtained at a 50:50 blend ratio of sugarcane bagasse to cassava rhizome and a pyrolysis temperature of 550°C. At this optimal condition, the corresponding biochar and biogas yields were 16.2% and 47.6%, respectively. The **thermal conversion efficiency** of the pyrolysis process under these conditions was calculated to be approximately 76**%,** indicating effective energy recovery from the feedstock**s.** Future investigations are recommended to explore other lignocellulosic biomass types, such as feedstocks, particularly within free-fall reactor systems.

Acknowledgement

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