

SUSTAINABLE CONVERSION OF AGRICULTURAL WASTE: BIO-OIL PRODUCTION FROM CASTOR STALK VIA PYROLYSIS

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This study investigates the potential of castor stalk, an abundant agricultural residue in Gujarat, India, as a feedstock for sustainable bioenergy production through pelletization and pyrolysis. The castor stalk was processed and characterized to determine its proximate and ultimate composition, bulk density, and higher heating value. Pelletization significantly enhanced the energy density from 2665.66 MJ.m⁻³ to 7406.12 MJ.m⁻³. Pyrolysis experiments were conducted in a batch-scale pyrolyzer across a temperature range of 400 °C to 600 °C. The optimal temperature for maximum bio-oil yield (42.80 wt. %) was found at 450 °C, accompanied by bio-char (33.60 wt. %) and pyro-gas (23.60 wt. %) production. Gas chromatography analysis revealed the presence of energy-rich gases such as H₂, CO, and CH₄ in the pyro-gas, with a maximum higher heating value of 14.80 MJ m⁻³. The bio-char exhibited both favourable fuel properties and potential for use in agriculture and industrial applications. Overall, the study demonstrates the viability of castor stalk as a cost-effective and renewable biomass source for thermochemical conversion into valuable biofuels.

Keywords: agriculture waste, castor stalk, bio-oil, gas, bio-char, pyrolysis

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1. Introduction

The increasing demand for sustainable energy and environmentally friendly materials has driven significant interest in agricultural residues as renewable resources. Among these, castor stalks—by-products of castor oil production from the *Ricinus communis* plant—represent a promising yet underutilized waste feedstock. India is the world's leading producer of castor, with Gujarat alone contributing approximately 85% of national production. Following seed harvesting, a substantial volume of waste castor stalk biomass becomes available, particularly during the post-harvest period between December and March.

Castor stalks are structurally composed of xylem (83.95 % by weight), cortex, and pith, making them suitable for applications in bioenergy, bio-composites, and organic fertilizers. Their chemical composition—rich in cellulose, hemicellulose, and lignin—further enhances their potential for value-added utilization through thermochemical and biochemical conversion processes [1,2].

Geographically, Gujarat remains the most significant contributor to castor biomass, with key producing districts including Banaskantha, Kutch, Patan, Mehsana, and Surendranagar [3]. After harvest, castor stalks are abundantly available in these regions and serve as a readily accessible biomass resource.

The valorization of castor stalks has been explored across various domains. They can be thermochemically converted into biofuels through pyrolysis, gasification, and combustion, yielding bio-oil, biochar, and syngas [4]. Additionally, lignin extracted from castor stalks is suitable for catalytic depolymerisation into aromatic monomers, which have industrial relevance [5]. Other

applications include composting with castor shells to produce nutrient-rich organic manure [6], fiber production, bioethanol generation, and usage as livestock bedding or agricultural mulch.

Among the conversion pathways, pyrolysis and gasification are particularly promising due to their ability to produce high-energy outputs. Pyrolysis at elevated temperatures (250–500°C) enhances the yields of bio-oil and pyro-gas while reducing biochar content [7]. Gasification, on the other hand, produces synthesis gas (CO and H₂), which can be directly used as a fuel or converted into liquid biofuels such as methanol and ethanol.

Given their abundance, composition, and versatility, castor stalks offer an opportunity for integrated bioresource utilization. This study aims to evaluate the thermochemical conversion potential of castor stalks, focusing on process optimization and analysis of all products to support sustainable energy strategies in agricultural regions. The increasing demand for sustainable energy and environmentally friendly materials has driven significant interest in agricultural residues as renewable resources. Among these, castor stalks—by-products of castor oil production from the *Ricinus communis* plant—represent a promising yet underutilized waste feedstock. India is the world's leading producer of castor, with Gujarat alone contributing approximately 85% of national production. Following seed harvesting, a substantial volume of waste castor stalk biomass becomes available, particularly during the post-harvest period between December and March.

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2. Methods

2.1. Materials Procurement and Preparation

Castor stalks used in this study were procured from Suri Farm, located in Kalsar village, Thasra, Kheda district, Gujarat, India. As an abundant and low-cost agricultural residue in the region, castor stalks represent a promising waste feedstock. First, the Castor Stalk were dried in the sun, ground using a hammer mill, and sieved through a mesh of size 10 to remove larger impurities like sand, dust etc. The resulting material had a uniform particle size of ≤ 2 mm and was used for all subsequent analyses and pyrolysis experiments.

2.2. Methods used for Material Characterization

2.2.1 Proximate Analysis, Bulk Density, and Calorific Value

Proximate analysis was performed according to standard ASTM methods:

- Moisture content: ASTM E871
- Ash content: ASTM D1102
- Volatile matter: ASTM E872
- Fixed carbon: by difference

These analyses were conducted at the Thermo-Chemical Conversion Division, Sardar Patel Renewable Energy Research Institute (SPRERI), Gujarat. Moisture content was measured using an infrared moisture analyzer (Sartorius® MA 100Q, Germany). A muffle furnace with PID temperature control was used for ash and volatile matter determination.

Bulk density was measured following ASTM E873-06. The higher heating value (HHV) was determined using an automated bomb calorimeter (IKA® C 5000, Cole-Parmer®, USA) at SPRERI.

2.2.2 Ultimate Analysis

Ultimate analysis (C, H, N, S and O content) was carried out using an elemental analyzer (2400 Series II, Perkin Elmer, USA) at the Sophisticated Instrumentation Centre for Applied Research and Testing (SICART), Vallabh Vidyanagar, Anand, Gujarat.

2.2.3 Thermogravimetric Analysis (TGA)

Thermal degradation behavior of the castor stalk was analyzed via thermogravimetric analysis (TGA) using a Pyris-1 TGA system (Perkin Elmer, USA) under a nitrogen atmosphere (sensitivity: 0.0001 mg, 50 mL/min.). Approximately 10 mg of the sample was heated from 50 °C to 1000 °C at a constant heating rate of 10 °C/min. Experiments were conducted at SICART.

2.3. Batch-Scale Pyrolysis

A batch-scale pyrolysis system (capacity: 0.5 kg) installed at SPRERI was employed for the thermal conversion experiments (Fig. 1). The reactor was constructed from stainless steel (SS304) and surrounded by a cylindrical electric heater to maintain the desired temperature. Biomass was fed into the reactor through a hopper, and an internal stirrer ensured uniform mixing. An inert atmosphere was maintained by continuous purging with nitrogen gas.

The pyrolysis vapors passed through a double-pipe heat exchanger, where chilled water (~10 °C) was circulated to condense the condensable fractions. The non-condensable gases were directed to a burner for safe combustion. Each pyrolysis experiment was conducted using 0.5 kg of castor stalk under the following constant parameters:

- Heating rate: ~40 °C.min⁻¹
- Nitrogen flow rate: 100 mLmin⁻¹
- Chilled water temperature: ~10 °C

The pyrolysis experiments were conducted in fine independent repetitions at each investigated temperature to ensure reproducibility of the experimental results.

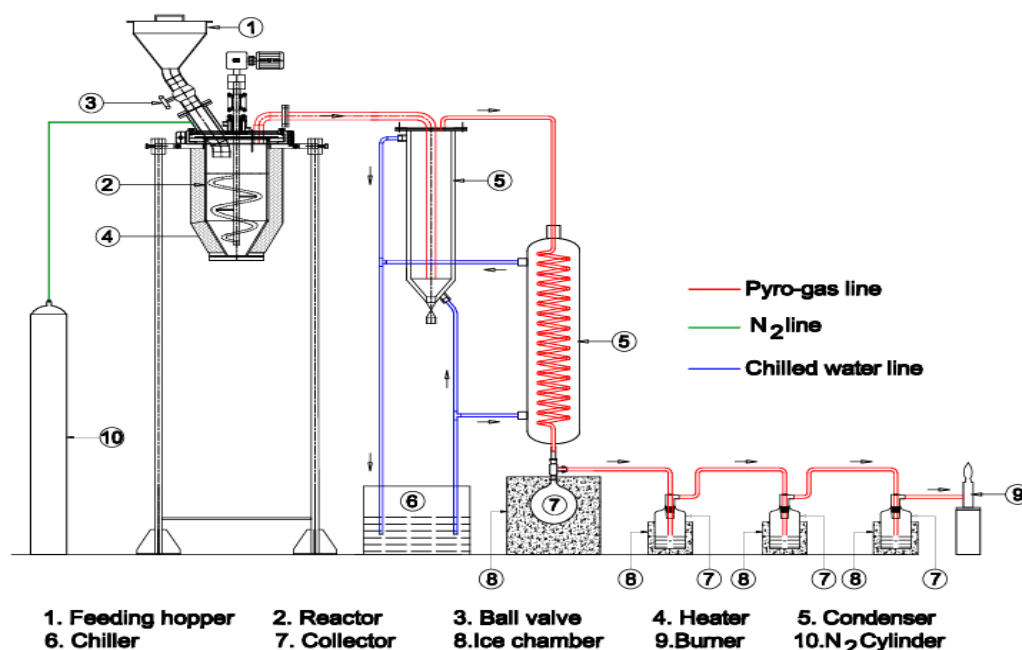


Fig. 1. Schematic diagram of the batch-scale pyrolysis system

2.4. Pyrolysis Products Characterization

2.4.1 Biochar

The biochar was analyzed using the same procedures and instruments described for the raw castor stalk in section 2.2. Proximate and ultimate analysis, bulk density, and higher heating value were measured to determine the physical properties and elemental composition of the biochar.

2.4.2 Bio-Oil

The bio-oil collected from the condenser was initially separated into aqueous and organic phases. First, the bio-oil was stored for 12 to 18 hours in conical vessel, allowing the viscous organic fractions to sink to the bottom while the lighter, water-rich aqueous fraction floated to the top. Next, 15 g of biooil was added in to 200 ml 1:1 solution of dichloromethane/methanol solution, which was then stirred for 5 minutes using a magnetic stirrer to ensure thorough mixing. The entire solution was passed through a 1.6-micron filter paper using vacuum filtration. Following this process, the solvent was removed from the oil through drying, and the filter paper was dried in an oven at 110°C for 30 minutes to determine the final solid content.

The organic phase was further dried using sodium sulfate (Na₂SO₄) to eliminate residual moisture. The moisture-free organic phase was subjected to the following analyses:

- pH: Measured using a pH meter (pH Tutor, Eutech Instruments, Singapore)
- Density: Measured using standard procedures at SPRERI

- Higher Heating Value: Measured using the automated bomb calorimeter (IKA® C 5000, Cole-Parmer®, USA)

Further molecular and structural characterization of the bio-oil was performed at SICART using:

- Fourier Transform Infrared Spectroscopy (FT-IR): Spectrum GX FT-IR (Perkin Elmer, USA)
- Nuclear Magnetic Resonance (NMR): ¹H and ¹³C, 400 MHz FT-NMR (AVANCE-III, Bruker, USA)
- Gas Chromatography–Mass Spectrometry (GC-MS): AutoSystem XL with TurboMass (Perkin Elmer, USA)

2.4.3 Pyro Gas

The non-condensable gases exiting the condenser were directed through a series of ice-cooled chambers, where condensable fractions were progressively condensed and separated. The remaining pyro-gas stream was subsequently routed to the burner for combustion. Prior to combustion, representative gas samples were collected for combustion analysis. The gas composition was determined using Gas Chromatography–Mass Spectrometry (GC-MS): AutoSystem XL with TurboMass (Perkin Elmer, USA), ensuring accurate identification and quantification of the volatile components.

3. Results and Discussion

3.1. Proximate Analysis of Castor Stalk

Proximate analysis was conducted to determine the moisture content, ash content, volatile matter, and fixed carbon content of castor stalk pellets. The results are presented in Table 1.

Table 1. Proximate Analysis of Castor Stalk

Parameter	Result
Moisture (wt. %)	3.40
Ash (wt. %)	8.20
Volatile Matter (wt. %)	68.60
Fixed Carbon (wt. %)	19.80

Proximate analysis of raw castor stalk, Fixed Carbon (FC), Volatile Matter (VM) and Ash content: 16.58 wt. %, 76.62 wt. % and 6.80 wt. % reported by Dobariya et.al (2022) [7], from proximate analysis Ash content was 2.3 wt. % reported by Shah et.al [8]. Similar result of proximate analysis of raw castor stalk, Fixed Carbon (FC), Volatile Matter (VM) and Ash content: 19.06 wt. %, 72.63 wt. % and 8.30 wt. % reported by Kelaiya et al [9]. Similar result of proximate analysis of raw castor stalk, Fixed Carbon (FC), Volatile Matter (VM) and Ash content: 9.16 wt. %, 74.30 wt. % and 5.40 wt. % respectively was reported by Kaur et.al (2018) [10]. Fixed Carbon (FC), Volatile Matter (VM) and Ash content: 21.09 wt. %, 53.75 wt. % and 19.02 wt. % respectively was reported by Deshannavar et.al (2017) [11]. Fixed Carbon (FC), Volatile Matter (VM) and Ash content: 16.58 wt. %, 76.62 wt. % and 6.80 wt. % was reported by Kaur et.al (2018) [12].

3.2. Ultimate Analysis of Castor Stalk

Ultimate analysis was conducted to determine the elemental composition of the biomass, as shown in Table 2. This analysis is critical in evaluating the suitability of biomass for thermochemical conversion processes, particularly in determining its combustion and emission behavior similar result of ultimate analysis is represented on table 3.

Table 2. Ultimate Analysis of Castor Stalk

Parameter	Result
C (wt. %)	46.20
H (wt. %)	6.40
N (wt. %)	1.20
O (wt. %)	46.20
H/C Ratio	0.138
O/C Ratio	1.0
N/C Ratio	0.025
Empirical Formula	$\text{CH}_{0.1351}\text{O}_{1.1328}\text{N}_{0.0382}$

Table 3. Ultimate Analysis of Castor Stalk

C wt. %	H wt. %	N wt. %	O wt. %	S wt. %	Reference
43.13	6.28	0.88	19.49	0.12	[11]
43.59	5.56	4.69	46.16	-	[12]
43.58	4.98	0.21	53.07	0.16	[13]

3.3. Physical Properties of Castor Stalk

Table 4. Energy Properties of Castor Stalk

Parameter	Value
Calorific Value (MJ.kg^{-1})	17.10
Bulk Density (kg.m^{-3})	0.20
Energy Density (MJ.m^{-3})	6501.42

Calorific value of castor stalk 14.43 MJ.kg^{-1} was reported by Kaur, R et.al (2018) [12] and 15.10 MJ.kg^{-1} was reported by Y. Elhenaway et.al (2024) [13].

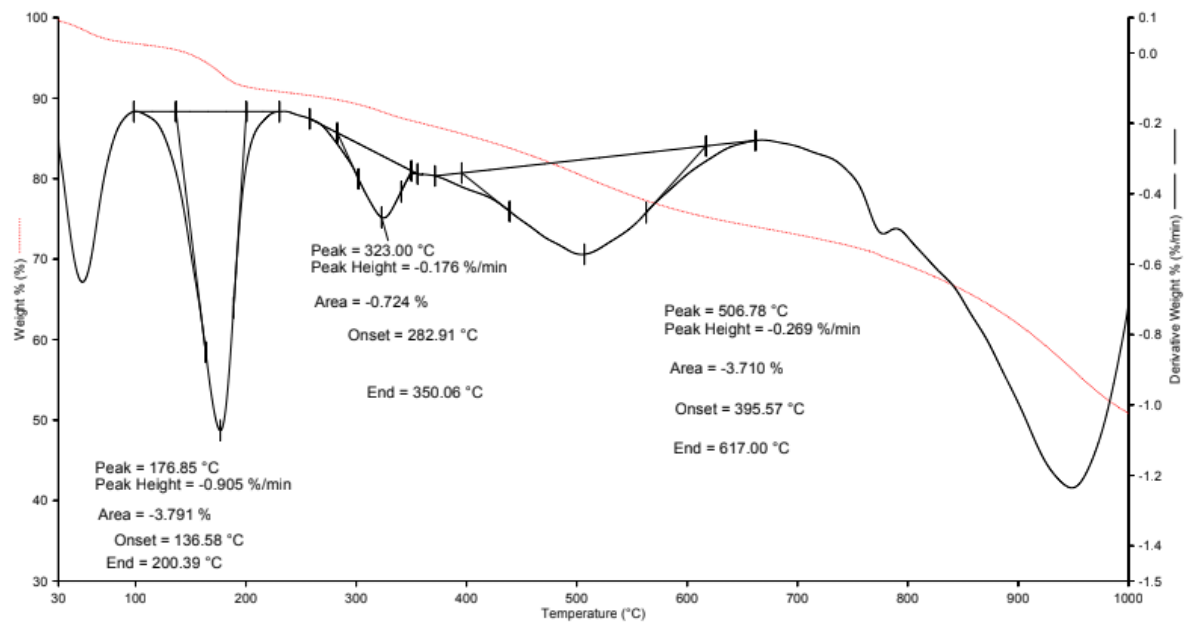


Fig. 2 TGA-DTG analysis of Castor Stalk

3.4. TGA analysis

Thermogravimetric analysis was conducted to evaluate thermal stability and decomposition behavior of biomass material. The TGA curve and its derivative profile provide insight into the weight loss characteristics as a function of temperature. Three distinct thermal events were observed, corresponding to different stages of biomass degradation.

Initial Devolatilization

The first major event occurred at 176.85 °C, with an onset at 136.58 °C and completion at 200.39 °C, resulting in a weight loss of approximately 3.79%. This stage is attributed to the removal of physical absorbed moisture and low molecular weight volatiles.

Hemicellulose/cellulose Decomposition

A second major event occurred at 323 °C with a weight loss of 0.72%. This transition corresponds to the partial breakdown of hemicellulose and cellulose fraction, releasing light volatiles.

Major Structural Decomposition

The third and most significant event occurred at 506.78 °C, spanning from 395.57 °C to 617 °C with a weight loss of 3.71%. This broad peak reflects the degradation of lignin and other stable organic structures, leading to formation of bio-oil vapors permanent gas.

3.5. Pyrolysis Study

Pyrolysis, a thermochemical process that converts biomass into valuable products in the absence of oxygen, was conducted across a temperature range of 400–600 °C.

3.5.1 Determination of Optimization of Pyrolysis Temperature

Pyrolysis of castor stalk was carried out at five different temperatures. The maximum yield of bio-oil

was achieved at 450 °C. The distribution of products is presented in Table 5.

Table 5. Product Yield at Different Pyrolysis Temperatures

Temperature (°C)	Bio-char (wt. %)	Bio-oil (wt. %)	Pyro-gas (wt. %)
400	38.40	33.20	28.40
450	33.60	42.80	23.60
500	28.20	37.20	34.60
550	22.60	28.20	49.20

- Bio-char yield decreases with increasing temperature.
- Pyro-gas yield increases consistently with temperature.
- Bio-oil yield increases up to 450 °C, after which it starts to decline.

Pyrolysis of castor stalk at 500 °C for 180 min produce 30.21 wt. %, 17.80 wt. % and 51.9 wt. % of bio-char, bio-oil and pyro-gas respectively was reported by Kaur et. al (2024) [14] Pyrolysis of bagasse at 400 °C generated 42 % of bio-oil was reported S. Agrawal et. al [15]. Pyrolysis of a wood biomass residue having particle size of 1 cm and a heating temperature of 480 °C generated bio-oil, syngas, and biochar yields are 38 wt. %, 22 wt. %, and 40 wt. %, respectively was reported Soni et. al (2024) [16]. Pyrolysis of lemon grass was generated bio-oil 37.3 wt. % with a biochar yield of 31.6 wt. % at 400 °C yang et. al (2024) [17]. Pyrolysis of pellets made from bending groundnut shell with crude glycerol was reported that Pyro-gas yield increased from 28 wt. % to 32 wt. % in batch scale as glycerol content increased by Parmar et.al (2023) [18].

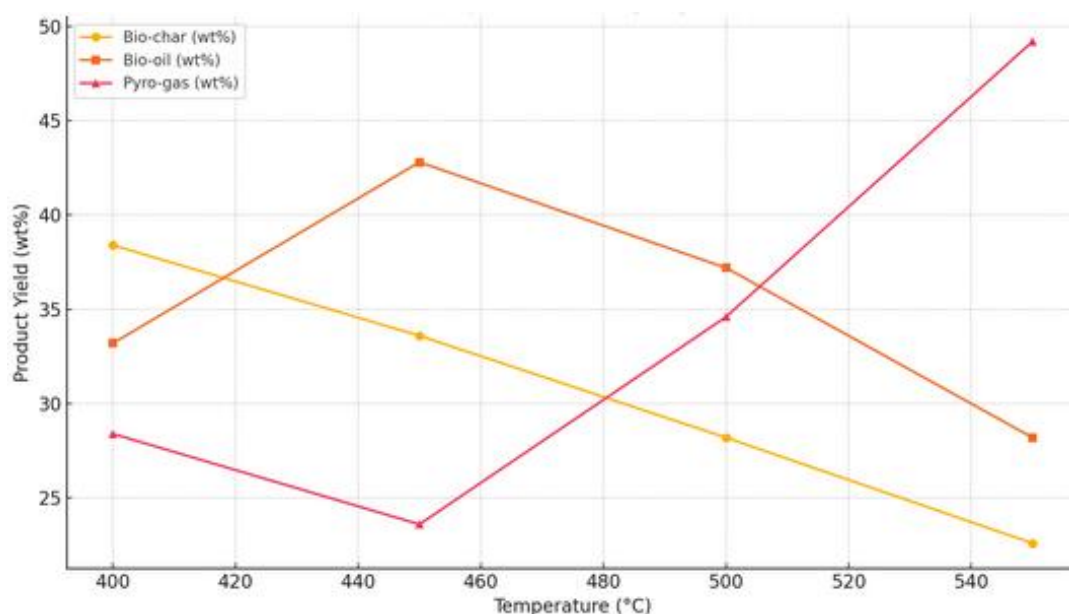


Fig. 3. Product yields at different pyrolysis temperatures.

At the optimal temperature of 450 °C, the yields were:

- Bio-char: 33.60 wt. %
- Bio-oil: 42.80 wt. %
- Pyro-gas: 23.60 wt. %

These results suggest that 450 °C is the most favorable pyrolysis temperature for maximizing bio-oil yield from castor stalk. The bio-oil can be utilized in industrial boilers and chemical production, bio-char can serve in agriculture and activated carbon production, and pyro-gas may be recirculated as a fuel in the pyrolysis system.

3.5.2 Pyro-Gas Characterization

Gas chromatography was employed to analyze the composition of pyro-gas generated at different temperatures. Results are shown in Table 6.

The highest calorific value of the pyro-gas (14.80 MJ.kg⁻¹) was observed at 550 °C. These values are

comparable to previous studies. For instance, Yang et al. [17] reported a calorific value of 7.27 MJ.kg⁻¹ from wood pellet pyrolysis at 450 °C, with gas compositions including CO (34.7 %), CH₄ (7.2 %), and CO₂ (50.27 %). Similarly, Soni and Karmee [16] reported high CO (54.23 %) and CH₄ (8.02 %) content from sawdust pyrolysis.

Table 6. Pyro-Gas Composition and Heating Value

Temp (°C)	H ₂ (%)	O ₂ (%)	N ₂ (%)	CH ₄ (%)	CO (%)	CO ₂ (%)	Calorific value (MJ.m ⁻³)
400	4.20	0.20	46.20	11.20	21.60	16.60	8.80
450	8.20	0.10	45.60	13.20	26.10	6.80	10.60
500	11.20	0.08	48.10	16.80	21.10	2.72	13.20
550	13.10	0.04	47.40	19.20	17.60	2.66	14.80
600	15.10	0.01	46.60	21.50	14.10	2.60	14.30

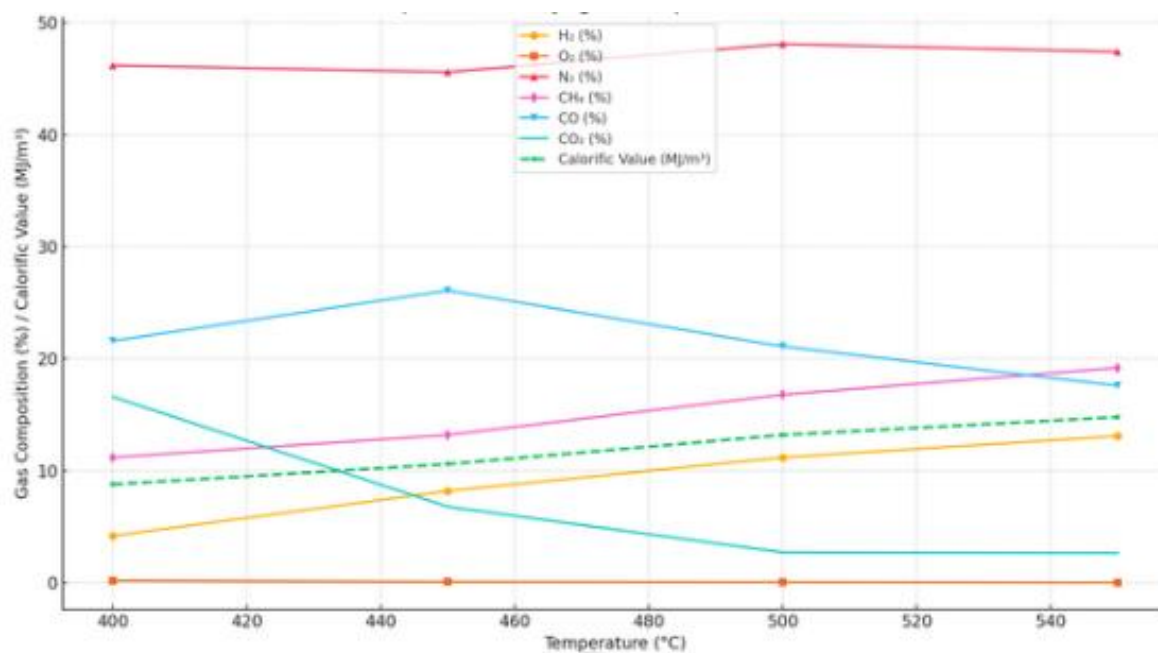


Fig. 4. Effect of temperature on pyrolysis gas composition

4. Conclusions

In this study, castor stalk biomass was evaluated as a potential feedstock for bioenergy production through pelletization and pyrolysis. The following key conclusions can be drawn from the experimental results:

- Proximate analysis revealed that castor stalk pellets possess a moderate moisture content (2.33 wt. %) and a relatively high volatile matter content (72.45 wt. %), indicating good suitability for thermochemical conversion. The addition of glycerol further increased the volatile matter, suggesting a higher potential bio-oil yield.
- Ultimate analysis showed a carbon content of 43.36 wt. % and an empirical formula of

CH_{0.1351}O_{1.1328}N_{0.0382}, which is favourable for fuel applications.

- Energy characterization demonstrated that pelletization significantly increased the bulk and energy density of the biomass, from 2665.66 MJ.m⁻³ (loose form) to 7406.12 MJ.m⁻³. This enhancement improves transport, handling, and storage efficiency.
- Pyrolysis experiments conducted between 400 °C and 600 °C revealed that the optimal temperature for maximum bio-oil yield was 550 °C, producing 33.00 wt. % bio-oil, 37.20 wt. % bio-char, and 29.80 wt. % pyro-gas. This temperature also achieved a balanced output of useful by-products.

- Pyro-gas characterization indicated the presence of combustible gases such as hydrogen, methane, and carbon monoxide. The maximum calorific value of 9.40 MJ m^{-3} was obtained at 450°C and 550°C , confirming the energy potential of the pyro-gas.

Overall, the results demonstrate that castor stalk, a readily available agricultural residue, can be effectively valorized via pelletization and pyrolysis into valuable energy products—bio-oil, bio-char, and pyro-gas. These products have multiple applications in energy, agriculture, and industry. This study supports the potential of castor stalk as a viable and sustainable bioenergy resource.

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