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Clovis Góis de Lacerda Filho
IFPE: Instituto Federal de Educacao Ciencia e Tecnologia de Pernambuco
Clériston Moura Vieira Júnior
cleriston.vieira@ufpe.br
Federal University of Pernambuco: Universidade Federal de Pernambuco https://orcid.org/0000-0002-5424-6378
Humberto da Silva Santos
University of Pernambuco: Universidade de Pernambuco
Shirlene Tamires Oliveira dos Santos
University of Pernambuco: Universidade de Pernambuco
Antonio Celso Dantas Antonino
Federal University of Pernambuco: Universidade Federal de Pernambuco
Daniel Milian Pérez
Federal University of Pernambuco: Universidade Federal de Pernambuco
Raquel Milani
Federal University of Pernambuco: Universidade Federal de Pernambuco
Sérgio Peres
University of Pernambuco: Universidade de Pernambuco

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Clovis Góis de Lacerda Filho [a], Clériston Moura Vieira Júnior [b,d], Humberto da Silva Santos [b], Shirlene Tamires Oliveira dos Santos [c,d], Antonio Celso Dantas Antonino [d], Daniel Milian Pérez [d], Raquel Milani [d], Sérgio Peres Ramos da Silva [b]

[a] Federal Institute of Education, Science and Technology of Pernambuco – IFPE, Department of Mechanical Engineering. Av. Professor Luiz Freire, n. 500, Cidade Universitária, Recife, Pernambuco, Brasil. CEP: 50.740-540. E-mail: lacerdac@elogica.com.br ORCID: https://orcid.org/0009-0002-6417-3712

[b] University of Pernambuco – UPE, Department of Mechanical Engineering. Polytechnic School of Pernambuco – POLI, Rua Benfica, 455 - Madalena, Recife, Pernambuco, Brasil. CEP: 50.720-001. E-mail: cleristonvieirajr@gmail.com, humberto.s.santos@hotmail.com, sergperes@gmail.com ORCID: https://orcid.org/0000-0002-5424-6378, https://orcid.org/0000-0002-0297-1834, https://orcid.org/0000-0002-2235-3507

[c] University of Pernambuco – UPE, Department of Electrical Engineering. Polytechnic School of Pernambuco – POLI, Rua Benfica, 455 - Madalena, Recife, Pernambuco, Brasil. CEP: 50.720-001. E-mail: shirlene.tamires@hotmail.com ORCID: https://orcid.org/0000-0002-4245-9165

[d] Federal University of Pernambuco – UFPE, Department of Nuclear Energy, Av. Professor Luiz Freire, n. 1000, Cidade Universitária, Recife, Pernambuco, Brasil. CEP: 50.740-545. E-mail: antonio.antonino@ufpe.br, daniel.milian@ufpe.br,raquel.milani@ufpe.br, ORCID: https://orcid.org/0000-0002-4120-9404, https://orcid.org/0000-0002-3172-0508, https://orcid.org/0000-0001-8076-6118.

Abstract

The increasing demand for renewable energy sources has intensified due to concerns over fossil fuel depletion, price volatility, and environmental impacts. Although Brazil's energy matrix is largely clean and renewable, its

dependence on hydropower poses risks during adverse hydrological conditions. Biomass gasification presents a viable alternative, with bamboo (*Bambusa vulgaris*) standing out due to its high productivity and rapid growth. This study evaluates the feasibility of bamboo biomass gasification for fuel gas production, optimizing process parameters to enhance conversion efficiency and energy output. Gasification experiments were conducted in a laboratory-scale gasifier with indirect electric heating, testing leafless bamboo and total plant bamboo under different chip sizes, temperatures, and exposure times. The most favorable operating conditions were observed with leafless bamboo (6–13 mm chips) at 900°C for 3 minutes, producing 4.02 $Nm^3 \cdot kg^{-1}$ of fuel gas, an energy yield of 39.69 kJ, and a conversion efficiency of 29.34%. These findings suggest that bamboo gasification could contribute up to 820 GWh annually to Brazil's energy matrix, offering a sustainable, low-carbon alternative to diversify the country's energy sources.

Keywords: Syngas composition, Renewable fuel, Thermochemical conversion, Energy efficiency, Biomass valorization, Sustainable energy systems.

Introduction

The increase in demand for traditional fossil energy has accompanied the accelerated growth of the global economy, leading to a severe environmental problem: climate change (Aprianti et al. 2023; Wang et al. 2023b). The combustion of fossil fuels is one of the primary contributors to environmental pollution, as it releases gases such as CO_2, CO, CH_4, NO_x, and SO_x, which intensify the greenhouse effect, leading to global warming (Sahu et al. 2014; Safarian et al. 2019). In addition to damaging ecosystems, the continuous burning of these fuels depletes the ozone layer, threatening both plant and animal life. Furthermore, sulfur oxides (SO_x) emitted from fossil fuels contribute to acid rain, which harms soil, water sources, and biodiversity (Saidur et al. 2011; Sahu et al. 2014). Beyond environmental concerns, fossil fuels present economic and geopolitical risks. These energy sources are finite, and their gradual depletion will inevitably lead to higher costs and market instability (Saidur et al. 2011; Tanger et al. 2013). The volatility of fossil fuel prices is also influenced by geopolitical conflicts, particularly in oil-producing regions such as the Middle East, causing fluctuations in global oil prices (Demirbas

2011). As fossil fuel availability diminishes, the cost of energy production is expected to increase, making conventional energy sources less viable for long-term use.

In recent years, global energy consumption has continued to rise, driven by population growth, industrialization, and technological advancements. According to the Statistical Review of World Energy 2024, primary energy consumption increased by 2% in 2023, surpassing its pre-pandemic levels by more than 5%. Despite this growth, fossil fuels still accounted for 81.5% of the global energy mix, reflecting only a 0.4% decrease from the previous year. Even with the record expansion of renewable energy, fossil fuel dependency remains a major obstacle to decarbonization efforts. While renewables' share of total primary energy consumption reached 14.6%, this growth was not enough to counterbalance rising global emissions, which increased by 2.1% in 2023, exceeding 40 gigatons of CO_2 equivalent for the first time in history. The primary driver of this increase was the continued consumption of coal, oil, and natural gas, which—despite sustainability commitments—remained the backbone of the global energy system (Energy Institute 2024).

To address these challenges, a fundamental shift towards a low-carbon economy is essential. This transition requires the gradual replacement of fossil fuels with renewable and low-carbon energy sources These alternatives offer lower greenhouse gas emissions and contribute to a more sustainable energy matrix (Martins et al. 2023). However, achieving a carbon-neutral energy system requires not only technological advancements but also strong policy frameworks that promote clean energy adoption, reduce dependence on fossil fuels, and incentivize the efficient use of bio-based energy sources (Mohammad et al. 2022).

Among the various renewable energy sources, biomass is the only sustainable carbon resource capable of producing solid, liquid, and gaseous fuels, as well as other raw materials or chemicals, making it a viable alternative to fossil fuels (Lauri et al. 2014; Xu et al. 2019; Yogalakshmi et al. 2022; Wang et al. 2023a; Wei et al. 2023). Biomass-derived fuels have been extensively researched due to their abundance, renewability, and ability to reduce carbon emissions (Salem et al. 2018; Quan et al. 2023; Siripaiboon et al. 2023; Wang et al. 2023a).

Biomass can be converted into useful energy forms through various thermochemical processes, with gasification being one of the most promising technologies (Li et al. 2016; Sepe et al. 2016; Greencorn et al. 2023; Wang et al. 2023a). Gasification is a thermochemical process that converts biomass into a combustible

gas mixture, mainly consisting of hydrogen (H_2), carbon monoxide (CO), and methane (CH_4) (Kirkels and Verbong 2011; Salem et al. 2018; Wang et al. 2023a; Yang et al. 2023). This gas can be used for industrial heating, power generation, and synthetic fuel production. Additionally, it can serve as a feedstock for the production of liquid hydrocarbons through the Gas-to-Liquid (GTL) process, which converts syngas into fuels such as synthetic diesel and gasoline (Peres 1997). Biomass gasification is also recognized as a cost-effective and efficient way to generate renewable energy, as it operates in a self-thermal sufficient process, allowing for high conversion efficiency (Wang et al. 2023b). Moreover, this technology plays a key role in decentralized energy systems, enabling the use of agricultural and industrial residues to generate thermal and electrical energy, particularly in off-grid and rural areas (Bridgwater 1995; Difs et al. 2010; Edenhofer et al. 2013). Research and innovation efforts are continuously improving biomass gasification efficiency, focusing on optimizing thermodynamic cycles to enhance energy conversion and facilitate its commercial expansion (Saghir et al. 2018). The agricultural sector provides large quantities of solid biofuels, including harvest residues, forestry by-products, and dedicated energy crops (Scarlat et al. 2011; Fernández-Sarría et al. 2019). Among these resources, bamboo stands out due to its high biomass yield and adaptability, making it an attractive candidate for gasification. To assess the feasibility of biomass gasification, preliminary analysis of the feedstock's chemical composition and energy characteristics is crucial. These analyses help determine the efficiency of the thermochemical conversion process and evaluate the industrial applicability of the raw material (Zhang et al. 2013).

Bamboo is a woody grass belonging to the Poaceae family and is one of the fastest growing perennial plants in the world. It is naturally found in forests, rural areas, farms, and along riverbanks, with approximately 90 genera and 110 species globally (Londoño and Clark 2002; Zhou, GuoMo; Jiang, PeiKun; Mo 2009; Zhou et al. 2011; Cheng et al. 2022; Lombardo 2022; Odega et al. 2023; Siripaiboon et al. 2023). Its high adaptability allows it to thrive in diverse climates across all continents except Europe, at altitudes ranging from sea level to 4,300 meters. Beyond its rapid growth, bamboo has exceptional physical and mechanical properties, making it a lightweight yet durable material widely used in construction, furniture, and textiles. While extensively utilized in Eastern countries for centuries, its potential remains underexplored in Western regions (Presznhuk 2004). As a biomass source, bamboo shares characteristics with agricultural residues and forestry by-products, serving as a raw material for biofuels and value-added chemicals (Chieng and Kuan 2020; Kumar et al. 2021). Moreover,

its high carbon sequestration capacity enhances its role in sustainable energy systems and climate change mitigation, while its ecological resilience makes bamboo an abundant and underutilized biomass resource for renewable energy (Cheng et al. 2022; Odega et al. 2023). In recent years, bamboo has gained attention as a renewable biomass feedstock for energy applications, particularly in thermochemical processes like gasification. Its high biomass yield and rapid growth rate make it a promising alternative for fuel gas production, with studies evaluating its composition, gasification efficiency, and energy output (Fabiani et al. 2023). Some of these studies will be discussed below.

Qiu et al. (2024) investigated bamboo gasification in supercritical water using ReaxFF molecular dynamics simulation and experimental validation. The study analyzed the influence of various parameters on gasification efficiency and elucidated the reaction mechanisms, revealing that at 4,300 K and 5 wt% feedstock concentration, H_2 yield reached 85.6%. Nguyen (2024) investigated the integrated CO_2-hydrothermal carbonization (CO_2-HTC) and high-temperature steam gasification of bamboo feedstock to enhance its suitability for energy production. The CO_2-HTC treatment at 240°C improved fixed carbon content, bulk density, and heating value, leading to quicker conversion and higher gasification efficiency during subsequent steam gasification at 900°C. Compared to raw bamboo, CO_2-HTC bamboo produced syngas with a 2% increase in both H_2 and CO concentrations. Mu et al. (2024) investigated oxygen-blown steam gasification of various lignocellulosic biomasses, including bamboo wood, to evaluate hydrogen-rich syngas production. Gasification experiments were conducted at 800°C with controlled oxygen and steam flow rates in a tube furnace reactor system. Soybean straw exhibited the highest H_2 yield (28.96 $mol \cdot kg^{-1}$). Further optimization reduced the required temperature (750°C) and oxygen flow rate (10 $mL \cdot min^{-1}$), increasing H_2 yield to 30.86 $mol \cdot kg^{-1}$. Yu et al. (2024) investigated the thermal radiation characteristics of various biomass feedstocks, including bamboo, for concentrating solar gasification applications. The study measured reflectance spectra in the 200–2,500 nm range, calculated refractive indices and extinction coefficients, and modeled dielectric functions using the Kramers-Kronig relations and a 5th-order Lorentz oscillator model. The findings provide critical spectral property data to improve the design and optimization of solar-driven biomass gasification reactors, highlighting bamboo's optical properties and potential for efficient solar energy absorption in thermochemical conversion. Tri Setioputro et al. (2025) examined the effect of soaked biomass on gasification temperature performance in an open-downdraft gasifier, focusing on different biomass types, shapes, and sizes. The study found that soaked

hardwoods maintained a stable gasification zone above 800°C, while soaked softwoods experienced a significant temperature drop below 700°C. Notably, soaked bamboo and coconut shell enabled the gasifier to sustain temperatures exceeding 1,000°C. Escalante et al. (2025) investigated biomass (pine wood, bamboo, and spent mushroom substrate) and high-density polyethylene co-gasification, optimizing cold gas efficiency (CGE) and carbon conversion (CC) using the Taguchi method and artificial neural networks (ANNs). The study found that temperature and catalyst type were the most influential factors, with 850°C and PN_2 catalyst yielding the highest CGE (65.67%) and CC (86.78%). ANN models successfully predicted CGE (70.96%) and CC (99.61%) with high accuracy. Finally, Chen et al. (2025) optimized catalytic co-gasification of biomass and polyethylene (PE) waste in an oxygen-rich environment, using the Taguchi method and Box-Behnken Design. The study analyzed pine wood, palm kernel shell, and bamboo as feedstocks, finding that the PE ratio significantly impacts cold gas efficiency, while catalyst type strongly influences carbon conversion. ANNs models successfully predicted gasification performance with $R^2 > 0.97$.

In Brazil, bamboo has been identified as a promising renewable resource, with significant potential for biomass energy production. Recognizing its economic and environmental value, the Brazilian government established Federal Law No. 12,484, of September 8, 2011, which created the National Policy to Encourage the Sustainable Management and Cultivation of Bamboo (PNMCB) (Brasil 2011). This policy aims to promote bamboo cultivation through government initiatives and private sector involvement, encouraging its sustainable management, industrial use, and environmental conservation. The PNMCB provides incentives for bamboo production, including rural credit under favorable conditions, technical assistance, and certification of origin and quality. Additionally, it supports the development of bamboo-based production hubs, particularly in regions with natural bamboo stocks, small-scale agricultural units, and research centers focused on bamboo applications. Several studies have explored bamboo's potential in Brazil, particularly in energy applications (Gonçalves et al. 2023; Letichevsky et al. 2023; Junior et al. 2025; Leonídia et al. 2025). However, much of this research has focused on bamboo char, biochar, and pyrolysis-derived materials, which, while valuable for various industrial and technological applications, are not optimized for heat and power generation. Unlike gaseous fuels, char-based materials cannot be used in gas turbines or combined-cycle power plants, limiting their role in large-scale energy systems. This highlights the need for further research into bamboo gasification, which could provide a more versatile and efficient energy alternative for Brazil's renewable energy matrix.

Given this scenario, this study aims to evaluate the feasibility of bamboo gasification as an alternative for clean energy production. To achieve this, a series of gasification tests were conducted using a laboratory gasifier with indirect electric heating in a batch regime. The experiments analyzed key process variables, including feedstock type, sample mass, reactor temperature, residence time, and chip size. The objective was to assess the quality and quantity of the produced gases, their lower calorific value, and the best conditions for optimizing energy yield. The broader goal of this research is to contribute to the development and optimization of bamboo gasification, with a specific focus on its physical-chemical and energetic characterization, as well as evaluating the influence of harvest form and feedstock granulometry on gasification performance.

Materials and Methods

The experiments were conducted at the Laboratório de Combustíveis e Energia (POLICOM), University of Pernambuco (UPE). The study involved gasification experiments performed in three main stages: biomass preparation, characterization, and evaluation of the gasification process. The methodological steps included analyzing the physicochemical properties of bamboo feedstock, followed by laboratory-scale gasification tests to determine the effects of key operational parameters on gas production performance.

Biomass collection and preparation

For this research, two forms of bamboo biomass were utilized: leafless bamboo (LB) and total plant bamboo (TPB). LB refers to bamboo harvested without leaves or branches, whereas TPB includes leaves, branches, and stalks. The selected bamboo variety was *Bambusa vulgaris*, extensively cultivated in Northeastern Brazil, particularly in the states of Pernambuco, Paraíba, Alagoas, and Maranhão (Drumond and Wiedman 2017). The biomass was provided by Agrimex, a company belonging to the João Santos Industrial Group, known for having Brazil's largest bamboo reforestation areas. This variety, classified as a woody grass, is well-adapted to local agro-climatic conditions, resulting in high agricultural productivity. The raw material was collected from Cepasa factory, which processes bamboo provided by Agrimex and local small-scale planters. Approximately 100 kg of each feedstock type (LB and TPB) were initially gathered. The bamboo was pre-cut into chips approximately one inch in length and then divided using the quartering method according to the Brazilian standard NBR 10.007/2007. In this method, the biomass was evenly spread onto a plastic tarp, divided into four

equal portions, and one portion was selected and re-divided until an appropriate sample size for laboratory tests was achieved. The remaining material was stored for potential future use.

After collection and quartering, the representative samples of LB and TPB were prepared for laboratory tests and physicochemical characterization according to the ABNT NBR 6.932/1981 standard (Char – sampling and sample preparation). This standard specifies air drying followed by milling small volumes of material. Pulverization and homogenization were performed using a Marconi MA-48 micro-mill with horizontal rotor knives, ensuring uniformity by cutting biomass into smaller particles that passed through a sieve classifier. Particle size distribution was controlled using a sieve shaker manufactured by Bertel Indústria Metalúrgica LTDA, accommodating up to eight mesh sieves with adjustable vibration and timing control. Densification, when required for specific characterization tests, was carried out using a manual press to produce pellets with higher density than the original biomass.

Biomass characterization

Characterization of the biomass concerning chemical composition and energy properties is essential to better understand its gasification behavior. The primary characteristics determined for the raw biomass samples are presented in the first column of Table 1. For each parameter, the analysis was carried out following specific standards shown in the second column of the same table. Each laboratory test was repeated five times to determine the sample mean and the Confidence Interval (CI). The sample mean was obtained by dividing the sum of the individual observations by their number. The estimation error (EE), defined as the maximum distance between the point estimate and the actual parameter value, was calculated for a 95% confidence level using Student's t-distribution with γ degrees of freedom, where γ equals the number of repetitions minus one. Thus, the CI represents a range bounded by minimum and maximum values, within which the true population mean is estimated to lie (Barros Neto et al. 2010). The CI ensures that, statistically, the actual population mean will fall within this calculated range 95% of the time when considering an infinite number of samples.

Table 1 Standards for biomass characterization.

Features	**Methodology**

Granulometry	ABNT NBR NM 248/2003: Aggregates – Determination of granulometric composition.
Moisture content	ABNT NBR 14.929/2003: Wood – Determination of moisture content in wood chips – Oven-drying method.
Bulk or Fractional Density	ABNT NBR 6.922/1981: Char – Physical tests for determining bulk density.
Calorific power	ABNT NBR 8.633/1984: Char – Determination of calorific value – Bomb calorimeter test method.
Immediate composition	ABNT NBR 8.112/1986: Char – Proximate analysis – Test method.
Elementary composition	ASTM D5373/2008: Standard Test Methods for Instrumental Determination of Carbon, Hydrogen, Nitrogen, and Sulfur in Laboratory Samples of Coal.
Ash content	ASTM D4208/2007: Standard Test Method for Total Chlorine in Coal by the Oxygen Bomb Combustion/Ion Selective Electrode Method.
Bromatological analysis	Van Soest and Robertson Method (1985) (Van Soest et al. 1991)

Gasification experiments were performed in a laboratory-scale gasifier specifically designed to compare the performance of different biomass feedstocks under varying conditions. The equipment allowed adjustments to process parameters such as operating temperature, residence time, feedstock mass, and particle size (granulometry). These modifications facilitated the assessment of the gasification behavior and energy potential of bamboo biomass samples under different conditions, ensuring comparative evaluations. Additionally, the equipment enables rapid gasification of the analyzed raw materials, allowing for efficient collection of the generated combustible gases and residues, as well as simplified calculation of the produced gas volume.

System description and gasification conditions

A mini-gasifier (Figure 1) was used for the gasification tests, based on the design by (Peres 1997), with modifications and manufacturing by Socal Indústria Metalúrgica. This equipment is designed to compare the behavior of different raw materials in various forms, allowing modifications to process variables such as operating temperature, residence time, feedstock mass, and granulometry. The system enables rapid gasification, facilitating the efficient collection of combustible gases and residues, while also allowing for simplified volume calculations of the generated gases. The laboratory bench gasifier operates in batch mode, making it suitable for small-scale experiments, process parameter testing, and evaluation of underdeveloped feedstocks. Since the intermediates formed during gasification are not directly measured, process optimization relies on the inlet and outlet reactant concentrations, along with initial and final thermodynamic conditions. The batch system is particularly effective for laboratory testing, as it provides precise control over key variables (temperature, residence time, biomass type, sample mass, and particle size) to optimize fuel gas formation.

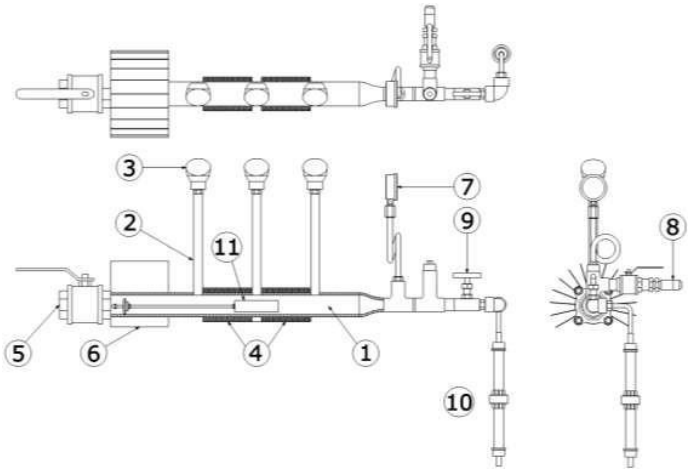


Fig. 1. Schematic drawing of the laboratory gasifier.

The equipment consists of a horizontal furnace, composed of the main piping (position 1) and connected to a set of secondary piping, valves, and measuring instruments. The furnace, constructed from seamless carbon steel tubing (ASTM A106, Grade A, Schedule 80), has a length of 760 mm, an outer diameter of 50.8 mm, and an inner diameter of 38.1 mm. Along the longitudinal axis of the furnace, three ASTM A106, Grade A, Schedule 40 carbon steel branches (position 2), each 300 mm long, are welded at 150 mm intervals (center to center). At the ends of these branches, three Type K thermocouples (position 3) are installed, ensuring that their sensor tips

are precisely positioned at the center of the main pipe for accurate temperature measurement. The main piping is surrounded by two stainless steel electrical resistors (position 4), which contain Kanthal D heating elements, each with a power rating of 1000 W. To prevent heat dissipation, the electric resistances and piping are wrapped in rock wool thermal insulation, which also provides electrical insulation for the resistors' connections. The central section of the reactor, which reaches the highest temperatures (above 900°C), is designated as the hot zone, where gasification occurs. At the front end of the gasifier, a stainless steel AISI 304 spherical valve (50.8 mm diameter) (position 5) serves as the sample injection port and is also used for residue removal after gasification. Adjacent to this valve, a finned heat sink made of AISI 316 stainless steel (position 6) facilitates cooling of both the piping and the spherical valve, allowing for safe sample handling by preventing excessive heating of the inlet valve. On the opposite side of the feeding valve, the main piping diameter reduces from 50.8 mm to 33.2 mm, leading to a welded tee fitting that accommodates a brass-threaded siphon tube, designed to protect the analog manometer (position 7) mounted on top. Additionally, a second tee connection is welded to mount a digital pressure transmitter (position 8), which continuously sends process signals to the control system. A ball valve is integrated into the system to allow for sensor maintenance when required. To regulate the discharge of process gases, a needle valve (position 9) is installed, ensuring controlled gas release and preventing pressure surges during experiments. This valve also enables countercurrent cleaning of the equipment using compressed air, facilitating new gasification cycles or introducing inert gases for pyrolysis tests, increasing the system's versatility. The produced fuel gas exits the system through a filtration unit (position 10) before being directed into a sample collection bag, where it is stored for qualitative analysis. Finally, during the experiment setup, the bamboo samples are placed inside the gasifier using a stainless steel AISI 304 container (position 11), ensuring precise placement within the hot zone, where the highest temperatures are reached for optimal gasification conditions.

To evaluate the gasification performance of bamboo biomass, 27 experiments were conducted under controlled conditions, systematically varying key parameters such as temperature, sample mass, residence time, biomass type, and granulometry. The gasification temperature was tested at three levels (700°C, 800°C, and 900°C) to assess its influence on gas composition and efficiency. The biomass sample mass used in the experiments was either 7 g or 9 g, ensuring a controlled comparison of feedstock quantity on reaction dynamics. The residence time in the gasifier was set at 3 or 5 seconds, allowing for an analysis of how exposure time affects the

conversion of biomass into fuel gases. The experiments also included two biomass types: LB and TPB. The granulometry of the biomass was classified into three particle size ranges: X < 6 mm, 6 mm < X < 13 mm, and 13 mm < X < 25 mm, to investigate the role of particle size in gasification efficiency. The combination of these variables allowed for a detailed evaluation of the gasification process under different operating conditions. The experimental conditions for each test are summarized in Table 2.

Table 2 Experimental conditions for bamboo gasification.

Experiment No.	Temperature [ºC]	Mass [g]	Time [s]	Biomass type	Granulometry range [mm]
1	700	7	3	LB	13 < X < 25
2	700	7	5	LB	13 < X < 25
3	700	7	3	LB	6 < X < 13
4	700	7	5	LB	6 < X <1 3
5	700	7	3	LB	X < 6
6	700	7	5	LB	X < 6
7	700	9	3	LB	13 < X < 25
8	700	9	5	LB	13 < X < 25
9	700	9	3	TPB	13 < X < 25
10	700	9	5	TPB	13 < X < 25
11	700	9	3	TPB	6 < X < 13
12	700	9	3	TPB	X < 6
13	800	9	3	LB	13 < X < 25
14	800	9	5	LB	13 < X < 25
15	800	9	3	TPB	13 < X < 25
16	800	9	5	TPB	13 < X < 25
17	800	9	3	LB	6 < X < 13
18	800	9	3	TPB	6 < X < 13
19	800	9	3	LB	X < 6

20	800	9	3	TPB	X < 6
21	900	9	3	LB	13 < X < 25
22	900	9	5	LB	13 < X < 25
23	900	9	3	LB	6 < X < 13
24	900	9	3	LB	X < 6
25	900	9	3	TPB	13 < X < 25
26	900	9	3	TPB	6 < X < 13
27	900	9	3	TPB	X < 6

Temperature and pressure monitoring, control, and data acquisition

To ensure precise monitoring of temperature and pressure in the gasifier, data acquisition was carried out using two myPClab dataloggers (Novus Produtos Eletrônicos), connected to a computer via USB cables. Temperature readings were obtained from three K-type thermocouples, strategically placed inside the furnace: one in the hot zone and two positioned 150 mm apart on either side. Pressure measurements were recorded using a 0–60 bar relative pressure transmitter, with data logging configured to capture readings every 500 milliseconds.

Furnace temperature control was managed by a PID compensator (model N1040, Novus Produtos Eletrônicos), which regulated heating based on real-time feedback from the primary K-type thermocouple in the hot zone. The system continuously compared the measured temperature with the setpoint, adjusting the power supply through two relays. When the temperature dropped below the desired level, the relays activated the electrical resistors, applying a voltage of 220 V to maintain heating. Conversely, if the temperature exceeded the setpoint, the relays cut off power, preventing further heating. The PID system dynamically modulated voltage application, ensuring stable and efficient temperature control.

Beyond ensuring stable temperature regulation, understanding the temperature distribution inside the gasifier is crucial for evaluating the thermodynamic conditions and gasification efficiency. Therefore, a detailed temperature distribution analysis was conducted along the furnace to determine the air molar quantity at different operating temperatures. Once the system reached a steady-state condition, a Minipa K-type thermocouple (model MT455) was inserted into the main piping, allowing temperature measurements at

multiple points along the reactor's longitudinal axis. These readings were taken at 20 mm intervals, covering the distance between the sample inlet ball valve and the gas release needle valve. This technique for calculating the number of moles of air as a function of temperature considers the air as a "molecule" and follows the Ideal Gas Law (Equation 1).

$$PV = nRT \quad (1)$$

where P represents atmospheric pressure, V is the volume of the considered section, R is the universal gas constant, n is the number of air moles, and T is the mean absolute temperature (in degrees Kelvin) of the section, given by:

$$T = \frac{T_{max}+T_{min}}{2} \quad (2)$$

Qualitative and quantitative analysis of the generated fuel gas

The experimental procedure began with sample preparation, where the masses of LB and TPB were weighed on an analytical balance. The biomass was then placed inside an AISI 304 stainless steel container equipped with positioning rods, ensuring precise placement in the hot zone of the gasifier. These rods facilitated both sample insertion and removal, particularly when handling the container at high temperatures. The gasifier required an average of 100 minutes to reach the target temperature before each experiment could begin.

Once the set temperature was stabilized, the sample container was inserted into the gasifier, and the injection ball valve was closed to isolate the reactor environment. The biomass was then gasified for the predetermined residence time. During the process, the needle valve remained closed to measure the maximum internal pressure of the generated gases. At the end of each gasification experiment, the reactor was cleaned to minimize contamination of the fuel gas with residues from previous tests. The cleaning process involved using a steel brush to remove solid residues, followed by compressed air injection through the gas outlet nozzle with the valves open, ensuring countercurrent cleaning of the equipment. This procedure effectively expelled residual gases and ensured that subsequent experiments were conducted under identical initial conditions. Once the reactor temperature stabilized again at the required test temperature, a new experiment could be initiated.

After the gasification period, the needle valve was carefully opened to release and collect the produced gases into plastic sample bags connected via a silicone tube to the gas cleaning filter outlet. To prevent contamination

with residual air, the sample bags were pre-purged using a vacuum pump. After collection, the gases were sent to the laboratory for qualitative composition analysis. Each experiment was performed in triplicate, allowing the calculation of the arithmetic mean and standard deviation.

In addition to the qualitative analysis, which determined the composition of the gases produced during bamboo gasification, a quantitative analysis was conducted to evaluate the volume of gases generated under different experimental conditions. This analysis was based on key process parameters, including biomass mass, gasification temperature, residence time, bamboo type, and granulometry. The quantitative assessment is essential, as it allows for the determination of the amount of gas produced per unit mass of raw material, as well as its calorific value. With this information, it becomes possible to estimate the total energy yield of the gasification process, providing a basis for its technical and economic feasibility as a renewable energy source.

The total gas volume generated during biomass gasification was determined using the pressure increase inside the reactor as an indirect measure. At the time of sample injection, the gasifier was at atmospheric pressure, since the injection ball valve remained open. As soon as the valve was sealed, the pressure inside the reactor began to rise due to gas formation. Given that the gasifier volume, internal temperature, and final pressure were known, the approximate gas volume produced in each experiment was calculated, assuming that both air and gas behaved as ideal gases, following the Ideal Gas Law (Equation 3).

$$R = constant = P_1V_1(n_1T_1)^{-1} = P_2V_2(n_2T_2)^{-1} \quad (3)$$

Indices 1 and 2 represent the initial and final states of the gasification process, respectively. Since the reactor volume and temperature remained constant, the increase in pressure was solely attributed to the increase in the number of gas moles, simplifying Equation 3 into Equation 4.

$$R = constant = P_1n_1^{-1} = P_2n_2^{-1} \quad (4)$$

From this, the normalized gas volume was calculated using the Ideal Gas Law (Equation 5).

$$n_2 = P_2n_1P_1^{-1} \quad (5)$$

Gas chromatographic analysis of combustible gases

To determine the qualitative and quantitative composition of the gases produced during the gasification experiments, two gas chromatographs were used. The first device, an SRI Instruments, model 8610C, was

equipped with a thermal conductivity detector (TCD) and a packed column from SGE (1/8-inch diameter and three meters long, with stationary phase, molecular sieve Mol Sieve5A). This chromatograph operated isothermally at 40 °C, using argon as the carrier gas at a flow rate of 20 mL·min^{-1}, and was used specifically to determine the hydrogen content in the synthesized gas samples. The second chromatograph, a Thermo-Scientific Trace model, was equipped with a TCD detector and a Restek capillary column (0.53 mm outer diameter, 30 meters long, 0.5 μm molecular sieve Mol Sieve 5A). This system used oven temperature programming, with the injector set at 200 °C with a 1:50 split, a transfer line temperature of 190 °C, and a base temperature of 200 °C. Hydrogen was used as the carrier gas at a flow rate of 3.5 mL·min^{-1}, and this chromatograph was responsible for determining the concentrations of hydrocarbons, carbon monoxide, and carbon dioxide in the gas samples.

For calibration and quantitative analysis, known molar quantities of reference gases were injected, representing the expected composition of gases found in biomass gasification. These included H_2, CO, carbon dioxide (CO_2), CH_4, ethane (C_2H_6), and ethene (C_2H_4). The amounts of injected gases were directly correlated with chromatogram peak areas, establishing a response curve that related the gas volume to the chromatographic area. This calibration method follows the principles of molar factor calculations as described by Ciola (1985). Once the number of moles of each gas was determined, it was converted into mass, and the mass percentage of each component was calculated by dividing the individual mass by the total mass of the sample, then multiplying the result by 100. This data was used to calculate the higher heating value (HHV) and lower heating value (LHV) of the produced fuel gas, using Equation 6.

$$HV\ of\ the\ mixture = \sum M_i \cdot HV_i \quad (6)$$

where M_i represents the molar fraction of each gas and HV_i is its respective heating value.

Energy and thermal efficiency analysis

To evaluate the energy potential of bamboo gasification, the total energy generated by the produced fuel gas was determined and compared with the energy content of the raw biomass. This analysis provides insights into the feasibility and efficiency of the gasification process for energy conversion. The total energy of the produced gas was determined by multiplying the lower heating value (LHV) of the gas by the total volume of gas generated during the gasification process, as expressed in Equation 7.

$$Total\ Energy\ [kJ] = LHV\ [kJ \cdot Nm^{-3}] \cdot Volume[m^3] \quad (7)$$

This total energy analysis is a valuable tool for comparing the energy potential of different gases produced during gasification. While gas volume and calorific value alone provide useful information, their combined analysis allows for a more comprehensive evaluation of the process efficiency. The thermal efficiency of the gasification process was determined by dividing the LHV of the gases by the LHV of the feedstock, as described in Equation 8.

$$\eta_{thermal} = LHV_{gas} \cdot LHV_{biomass}^{-1} \quad (8)$$

Thermal efficiency analysis is crucial for optimizing the gasification conditions to ensure maximum energy conversion from the biomass. By assessing these efficiency values, it is possible to determine the optimal parameters for achieving a higher energy yield, leading to a more sustainable and effective utilization of bamboo as a biofuel.

Results and discussion

Biomass Characterization

The characterization of bamboo biomass is essential to evaluate its suitability for gasification, as both physical and chemical properties influence the efficiency of thermochemical conversion. The particle size distribution of bamboo in its natural state (LB and TPB) is shown in Table 3. The results indicate that the largest fraction of bamboo chips passes through the 13-mesh opening and is retained in the 6-mesh opening, representing 39.19% of the total sample, with a characteristic size of 9.86 mm. The second most significant fraction consists of bamboo chips passing through the 25-mesh opening and being retained in the 13-mesh opening, with a proportion of 27.59% and a characteristic size of 19.55 mm. This distribution suggests that most bamboo particles used in the experiments had an intermediate size. According to Hagge & Bryden (2002), particle size plays a crucial role in tar formation during gasification, as smaller particles tend to generate higher tar content due to increased surface area available for pyrolysis. The observed distribution, therefore, is favorable for reducing excessive tar formation, which can enhance gasification efficiency.

Table 3 Bamboo particle size analysis results.

Mesh aperture	fi [kg]	fi [%]	Fi [g]	Fir [%]	size [mm]
25	0.392	9.78	392	9.78	27.48
13	1.106	27.59	1498	37.37	19.55
6	1.571	39.19	3069	76.56	9.89
Pan	0.940	23.44	4009	100	2.98

The proximate analysis (Table 4) provides insights into the composition of LB and TPB bamboo. The results indicate that TPB bamboo has a fixed carbon content 16% higher than that of LB bamboo, which may contribute to a longer residence time for combustion reactions and, consequently, influence syngas composition. Both biomass types exhibit high volatile matter content, with LB presenting 2.9% more volatiles than TPB. This high volatile fraction is beneficial for gasification, as it promotes rapid fuel gas release. On the other hand, the ash content was significantly higher in TPB (2.97%) compared to LB (1.26%), indicating a greater presence of inorganic components. Ash can have a negative impact on gasification by promoting slagging and fouling, potentially reducing reactor performance. The moisture content was also 8.6% higher in TPB, which could slightly affect the thermal efficiency of the process, although moderate moisture content can contribute to increased hydrogen production through steam reactions.

Table 4 Result of the proximate analysis of bamboo (on a dry basis).

Biomass	Bamboo LB	Bamboo TPB
Fixed Carbon	3.51 ± 0.69	4.08 ± 0.60
Volatiles	95.43 ± 1.67	92.74 ± 3.12
Ashes	1.26 ± 0.36	2.97 ± 0.81
Moisture	12.27 ± 3.12	13.32 ± 1.26

Further characterization through bromatological analysis (Table 5) shows that TPB bamboo contains 10.79% extractives, which is higher than the 8.43% found in LB. Extractives can influence the formation of volatile gases and secondary reactions in gasification. The cellulose and hemicellulose contents are similar for both bamboo types, with TPB showing a slightly higher hemicellulose fraction. Hemicellulose decomposes at lower temperatures, enhancing the early-stage formation of syngas. In contrast, LB bamboo has a higher lignin content (22.93%) compared to TPB (20.06%), indicating that LB may exhibit greater resistance to thermal degradation and require higher temperatures for effective conversion.

Table 5 Results of the bromatological analysis (on a dry basis).

Biomass	Bamboo LB	Bamboo TPB
Extractives	8.43 ± 0,76	10.79 ± 1.01
Cellulose	43.63 ± 2.19	42.27 ± 1.70
Hemicellulose	23.55 ± 1.08	24.06 ± 2.05
Lignin	22.93 ± 1.85	20.06 ± 1.20

The calorimetric analysis (Table 6) confirms that both LB and TPB bamboo possess similar higher heating values (HHV), with LB at 17.71 $MJ \cdot kg^{-1}$ and TPB at 17.52 $MJ \cdot kg^{-1}$. Similarly, the lower heating values (LHV) differ only slightly between the two types, demonstrating that bamboo is an energy-rich biomass with potential for gasification applications. These values align with those of other biomass types used for energy conversion.

Table 6 Results of the calorific value of bamboo. Heating Value [$MJ \cdot kg^{-1}$].

Biomass	Bamboo LB	Bamboo TPB
HHV	17.71 ± 0.15	17.52 ± 0.24

LHV	17.51 ± 0.16	17.29 ± 0.23

The bulk density of bamboo is an essential parameter for gasification, influencing handling, storage, and reactor performance. The results indicate that TPB bamboo has a bulk density of 278.64 ± 9.63 $kg \cdot m^{-3}$, which is 3.9% higher than that of LB bamboo (267.24 ± 9.74 $kg \cdot m^{-3}$). This difference is attributed to the presence of leaves in TPB, which fill the gaps between chopped stems and branches, increasing material compactness. A higher bulk density generally improves reactor efficiency by allowing more biomass to be packed into the gasification chamber, leading to greater energy output per unit volume.

The mass distribution of the bamboo fractions (Table 7) provides further insight into these differences. Field experiments showed that, on average, each bamboo plant weighed 20.98 ± 4.10 kg, with canes being the predominant fraction, representing 64.56% of the total mass. Branches accounted for 21.17%, while leaves made up the remaining 14.28%. Since the TPB biomass includes all plant fractions, it naturally contains a higher percentage of leaves compared to LB biomass, which consists mainly of stems. This composition difference is directly related to the higher ash content observed in TPB bamboo, as leaves typically contain more inorganic compounds than stems and branches.

Table 7 Mass of the fractions of the bamboo sample species *Bambusa vulgaris*.

Fractions	Mass (kg)	(%) ($m \cdot m^{-1}$)
Canes	13.62 ± 3.25	64.56
Branches	4.37 ± 0.58	21.17
Leaves	2.99 ± 0.56	14.28

The total ash content results (on a dry basis), measured using the muffle furnace method, further confirms this trend. TPB bamboo exhibits an ash content of 3.89 ± 0.34%, which is more than double that of LB bamboo (1.52 ± 0.13%). This confirms the trend observed in the proximate analysis, where TPB had a notably higher

inorganic fraction. Since excessive ash can cause operational challenges such as slag formation and clogging, LB bamboo appears to be the more favorable feedstock in terms of minimizing ash-related issues in gasification.

The elemental analysis (Table 8) provides further insight into the chemical composition of bamboo. The carbon content of LB bamboo is 1.2% higher than that of TPB, which could slightly improve its combustion efficiency and energy yield. Hydrogen content in LB bamboo is significantly higher (8.19%) compared to TPB (6.12%), which is an important factor in determining syngas composition and calorific value. Conversely, TPB bamboo exhibits a slightly higher nitrogen (0.76%) and sulfur content (0.32%), which could contribute to the formation of undesirable emissions such as NO_x and SO_x during gasification. The oxygen content, calculated by difference, is 5.63% higher in TPB. The H/C ratio is 28.6% higher in LB bamboo, suggesting a greater potential for hydrogen production in syngas. These results align with those obtained by R. Kumar & Chandrashekar, (2014) and Rousset et al. (2011).

Table 8 Elemental analysis of bamboo LB and TPB (*on a dry basis).

Biomass	Bamboo LB	Bamboo TPB
C	45.51 ± 0.06	44.97 ± 0.36
H	8.19 ± 0.24	6.12 ± 0.06
N	0.70 ± 0.06	0.76 ± 0.03
S	0.30 ± 0.06	0.32 ± 0.06
O*	45.29	47.84 ± 0.43
C/N	65.01	64.24
O/C	1.00	1.01
H/C	0.18	0.14

The calorific value of the bamboo samples was estimated using the Mendeleev equation, yielding values of 18.28 $MJ \cdot kg^{-1}$ for LB bamboo and 17.69 $MJ \cdot kg^{-1}$ for TPB bamboo. These estimates align well with the results

obtained in experimental tests, where the LHV were determined as 15.92 $MJ \cdot kg^{-1}$ for LB bamboo and 15.75 $MJ \cdot kg^{-1}$ for TPB bamboo. Additionally, when applying the Parikh et al. (2005) equation, the upper heating values (HHV) were estimated at 20.85 $MJ \cdot kg^{-1}$ for LB bamboo and 17.90 $MJ \cdot kg^{-1}$ for TPB bamboo, which closely match the experimentally determined values of 17.52 $MJ \cdot kg^{-1}$ for LB bamboo and 17.71 $MJ \cdot kg^{-1}$ for TPB bamboo. These results are consistent with those reported by Rousset et al. (2011), further validating the energy potential of bamboo as a feedstock for thermochemical conversion.

From the elemental composition of the biomass, the simplified molecular formulas for the two raw materials were determined as $C_{13}H_{28}O_{10}$ for LB bamboo and $C_{12}H_{20}O_{10}$ for TPB bamboo. The theoretical air demand for complete combustion was calculated using stoichiometric principles, resulting in 95.20 mol of air per mol of LB bamboo (Equation 9) and 80.92 mol of air per mol of TPB bamboo (Equation 10). These values reflect the oxygen demand of each biomass type and further highlight the higher hydrogen content in LB bamboo, which is advantageous for syngas production.

$$AC_{LB} = 20 + 20\ (3.76) = 95.20\ (\text{mol air} \cdot \text{mol fuel}^{-1}) \qquad \text{Eq. 9}$$

$$AC_{TPB} = 17 + 17\ (3.76) = 80.92\ (\text{mol air} \cdot \text{mol fuel}^{-1}) \qquad \text{Eq. 10}$$

The number of air moles inside the gasifier was calculated using the Ideal Gas Law, considering the experimental temperature distribution (Fig. 2) and the internal volume of the gasifier (1525 mL), which was determined both theoretically and through direct volume measurement. The results (Table 9) indicate that the number of air moles inside the gasifier decreased as temperature increased, following the expected inverse relationship between gas molar quantity and temperature in a closed system. Similar trends were observed by (Peres 1997) in previous gasification studies.

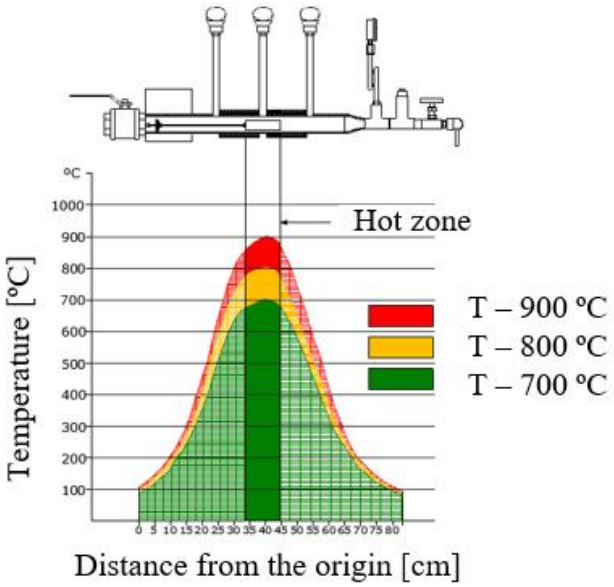


Fig. 2 Temperature distribution along the furnace at the temperatures of the experiments.

Table 9 Number of air moles inside the gasifier as a function of temperature in the hot zone.

Temperature in the hot zone [°C]	Number of moles of air
700	0.027902
800	0.025605
900	0.023904

The amount of biomass required for complete combustion was also estimated (Table 10), showing a slight decrease in required mass as temperature increased, due to improved reaction efficiency. However, the mass of bamboo injected during the experiments (7–9 g) was significantly higher than the stoichiometric requirement for complete combustion, confirming the substoichiometric conditions inside the gasifier. This controlled air deficiency is fundamental in establishing a reducing environment, which promotes the partial oxidation of biomass and facilitates the formation of syngas components such as H_2, CO, and CH_4, rather than complete oxidation to CO_2. This process is key to maximizing energy conversion efficiency and optimizing gasification

performance. The next section will examine the composition of the produced gases, energy yields, and overall thermal efficiency under different operating conditions.

Table 10 LB and TPB bamboo masses for complete combustion as a function of temperature in the hot zone.

Temperature in the hot zone [ºC]	Bamboo LB Mass (mg)	Bamboo TPB Mass (mg)
700	39	40
800	36	37
900	33	34

Gasification Performance and Fuel Gas Composition Analysis

The gasification process was evaluated based on the composition of the produced syngas, considering key components such as H_2, CO, CH_4, C_2H_6, and C_2H_4. Table 11 presents the gas values obtained under different experimental conditions.

Table 11 Gas composition obtained from the gasification of LB and TPB bamboo under different experimental conditions.

Experiment	H_2	CH_4	CO	C_2H_6	C_2H_4
	[% v/v]	[% v/v]	[% v/v]	[% v/v]	[% v/v]
1	16.79 ± 0.08	12.32 ± 1.10	11.46 ± 0.35	1.97 ± 0.04	1.24 ± 0.13
2	19.00 ± 1.09	13.91 ± 0.29	13.22 ± 2.77	1.68 ± 0.35	1.68 ± 0.35
3	18.98 ± 0.94	8.51 ± 0.58	8.66 ± 0.52	1.59 ± 0.25	0.87 ± 0.09
4	20.00 ± 0.82	10.13 ± 0.37	9.55 ± 0.62	1.86 ± 0.14	0.92 ± 0.04
5	18.62 ± 1.18	9.91 ± 0.59	9.27 ± 0.45	1.95 ± 0.04	0.93 ± 0.03
6	20.39 ± 0.89	12.42 ± 1.65	10.21 ± 0.62	1.90 ± 0.05	1.49 ± 0.25
7	21.08 ± 0.39	7.34 ± 0.36	15.34 ± 0.86	1.93 ± 0.13	0.84 ± 0.84
8	21.48 ± 0.11	8.19 ±0.32	17.03 ± 1.28	2.09 ± 0.21	1.87 ± 0.84

9	19.82 ± 0.28	6.28 ± 0.11	27.73 ± 0.92	1.64 ± 0.08	4.07 ± 0.15
10	20.19 ± 0.95	6.53 ± 0.28	28.48 ± 1.23	1.78 ± 0.12	4.26 ± 0.20
11	17.07 ± 2.67	5.59 ± 0.51	9.97 ± 0.76	1.38 ± 0.23	4.30 ± 1.16
12	18.39 ± 2.16	5.89 ± 0.64	8.37 ± 1.76	2.26 ± 0.90	4.39 ± 0.75
13	25.24 ± 1.38	10.38 ± 0.29	13.99 ± 0.77	0.99 ± 0.04	1.78 ± 0.17
14	26.10 ± 0.29	11.56 ± 0.05	14.59 ± 0.41	1.33 ± 0.36	2.49 ± 0.42
15	21.08 ± 0.39	7.14 ± 0.12	15.88 ± 0.72	1.92 ± 0.01	0.79 ± 0.15
16	21.39 ± 0.25	8.32 ± 0.22	17.45 ± 1.50	2.25 ± 0.12	0.94 ± 0.03
17	21.56 ± 1.91	8.04 ± 0.69	11.89 ± 0.35	1.62 ± 0.62	3.72 ± 0.29
18	22.41 ± 0,52	8.13 ± 0.49	12.33 ± 0.48	1.41 ± 0.04	2.49 ± 1.15
19	22.32 ± 1,51	10.15 ± 0.51	12.95 ± 0.45	1.31 ± 0.14	3.43 ± 0.02
20	21.66 ± 1,34	9.13 ± 0.51	11.18 ± 1.93	1.81 ± 0.31	0.01 ± 0.01
21	22.17 ± 1,01	5.29 ± 0.87	4.48 ± 1.23	0.82 ± 0.24	2.45 ± 0.58
22	22.51 ± 0,61	10.38 ± 0.48	13.26 ± 0.31	1.11 ± 0.05	2.42 ± 0.21
23	21.88 ± 1,13	11.51 ± 0.25	15.61 ± 1.05	1.28 ± 0.21	2.97 ± 0.97
24	20.42 ± 0,17	8.95 ± 0.52	12.23 ± 0.48	0.97 ± 0.19	6.18 ± 0.83
25	20.03 ± 2,03	10.27 ± 1.56	15.10 ± 1.72	0.95 ± 0.20	2.49 ± 0.37
26	20.94 ± 0,52	10.32 ± 0.15	13.74 ± 0.12	1.10 ± 0.15	2.99 ± 1.17
27	23.45 ± 0,43	7.75 ± 0.75	10.96 ± 1.44	0.64 ± 0.03	4.62 ± 1.19

Hydrogen was a predominant component in the syngas, with an average concentration of 20.93 ± 0.96% v/v across all experiments. The highest yield (26.10 ± 0.25% v/v) was obtained in Experiment 14, where LB bamboo with a particle size of 13–25 mm was gasified at 800°C with a 5-minute residence time and a 9 g sample mass. Notably, the hydrogen concentration was maximized at 800°C and 900°C, indicating that temperature plays a crucial role in hydrogen yield. These results align with literature findings, where increasing temperature enhances hydrogen production due to the promotion of endothermic reactions and cracking of hydrocarbons (Peres 1997; Kuo et al. 2014). However, variations in biomass type (LB or TPB) and particle size did not significantly impact H_2 production, as both feedstocks performed similarly. Likewise, gasification time did not

have a major influence, as similar hydrogen values were observed for different durations between 3 and 5 minutes. These observations are in agreement with studies on eucalyptus gasification, which reported minimal influence of particle size on hydrogen yield (Zanatta 2011).

Carbon monoxide was the second most abundant gas, with an average concentration of 13.52 ± 0.93% v/v. The highest CO content (28.48 ± 1.23% v/v) was recorded in Experiment 10, under the gasification of TPB bamboo with 13–25 mm particles at 700°C, a 5-minute residence time and a 9 g sample mass. Unlike hydrogen, CO formation was not highly dependent on temperature, as significant values were obtained across 700°C, 800°C, and 900°C. This result contrasts with the findings of Peres (1997), who, in experiments with sugarcane bagasse containing 5% moisture, observed an increase in CO concentration with rising temperature. Specifically, the average CO formation was 31.75% v/v at 700°C, 35.53% v/v at 800°C, and 37.50% v/v at 900°C. Particle size played a more relevant role, as experiments with larger chips (13–25 mm) yielded the highest CO concentrations. The biomass type also showed no fundamental variations in CO production, as both LB and TPB bamboo exhibited similar performance. Likewise, the gasification time also does not have a fundamental influence, since similar carbon monoxide formation values are found for different times.

Methane concentrations averaged 9.05 ± 0.53% v/v, with the highest value (13.91 ± 0.29% v/v) obtained in Experiment 2 (LB bamboo, 700°C, 13–25 mm particles, 5 minutes, 7 g sample mass). The results suggest that methane formation is influenced by biomass type, as LB bamboo consistently showed higher CH_4 yields compared to TPB bamboo. Additionally, residence time appears to be a determining factor, with 5-minute experiments yielding higher methane concentrations than shorter exposure times. The methane concentration values obtained are comparable to those reported in the literature for wood pellets, as shown in the research conducted by Liao et al. (2014), who reported an average methane concentration of 10.19% v/v in a pilot-scale fluidized bed gasifier. Similarly, Zanatta (2011) found average methane concentrations of 8.78% v/v. Finally, Peres (1997), in experiments with sugarcane bagasse containing 5% moisture, observed an increase in methane concentration with rising temperature, reporting an average formation of 9.14% v/v at 700°C, 11.42% v/v at 800°C, and 11.73% v/v at 900°C.

Ethane was found in lower concentrations, with an average value of 1.54 ± 0.19% v/v. The highest yield (2.26 ± 0.21% v/v) was observed in Experiment 12 (TPB bamboo, 700°C, particle size <6 mm, 3 minutes, 9 g sample

mass). The graph analysis indicates that the highest ethane concentrations were obtained when gasifying 7 and 9 grams of biomass at temperatures of 700°C and 800°C. Additionally, the particle size of the material plays a crucial role, as the best results were predominantly obtained with smaller chips (<6 mm). The type of feedstock does not appear to significantly impact ethane formation, as both biomass types were present among the highest-yielding experiments. Similarly, gasification time does not exert a fundamental influence, as similar ethane concentrations were recorded across different residence times.

Ethene concentrations averaged 2.47 ± 0.46% v/v, with the highest value (6.18 ± 0.83% v/v) occurring in Experiment 24 (LB bamboo, 900°C, particle size <6 mm, 3 minutes, 9 g sample mass). Similar to ethane, smaller particle sizes promoted ethene formation, reinforcing the role of surface area in enhancing secondary gas-phase reactions. Additionally, TPB bamboo showed a predominance among the highest ethene concentrations, suggesting that biomass type may have some influence. Gasification time also played a role, as most of the highest ethene yields were obtained with a 3-minute exposure time.

Regarding the ethane and ethene results, the amount of these gases generated in most experiments was lower than that of the primary fuel gases (H_2, CO, and CH_4) and fell within the same range as those reported in previous studies on sugarcane bagasse gasification (Peres 1997) and biomass waste gasification (Wenzel 2013). Peres (1997) reported ethane concentrations ranging from 0.90% v/v to 1.13% v/v, while Wenzel (2013) observed values around 0.72% v/v in leather waste gasification. Similarly, ethene concentrations varied from 1.55% v/v to 2.78% v/v in the study by Peres (1997), whereas Wenzel (2013) recorded values around 4.48% v/v. These results confirm that ethane and ethene are minor components in syngas compared to the dominant fuel gases produced in bamboo gasification.

Energy Performance and Industrial Implications

The energy potential of the syngas produced in the gasification experiments was assessed based on its lower heating value (LHV), total gas volume, energy yield, and thermal conversion efficiency. Table 12 presents the obtained values under different experimental conditions.

Table 12 Lower heating value (LHV), gas volume, char and ash content, total energy yield, and thermal conversion efficiency obtained from bamboo gasification under different experimental conditions.

Experiment	LHV	Volume of gas	Char + Ash	Energy	H
	($MJ \cdot Nm^{-3}$)	($m^3 \cdot kg^{-1}$)	(% m/m)	(MJ)	(%)
1	8.66 ± 0.38	1.22 ± 0.03	13.59 ± 1.19	8.19 ± 0.56	9.87 ± 0.08
2	9.36 ± 0.51	2.06 ± 0.05	13.56 ± 0.20	14.98 ± 1.12	18.19 ± 1.36
3	6.92 ± 0.21	1.28 ± 0.05	18.07 ± 0.82	7.07 ± 0.21	8.42 ± 0.56
4	7.81 ± 0.13	1.92 ± 0.04	18.07 ± 0.83	11.62 ± 0.42	14.18 ± 0.51
5	7.64 ± 0.25	1.20 ± 0.02	22.40 ± 1.29	7.07 ± 0.35	8.67 ± 0.34
6	8.99 ± 0.72	1.73 ± 0.01	22.41 ± 1.28	12.11 ± 0.91	17.74 ± 1.04
7	7.68 ± 0.14	2.29 ± 0.05	16.05 ± 0.34	17.64 ± 0.54	12.97 ± 0.41
8	8.80 ± 0.27	2.54 ± 0.06	16.04 ± 0.33	22.32 ± 1.08	16.45 ± 0.73
9	10.19 ± 0.19	1.75 ± 0.09	21.65 ± 1.97	17.82 ± 1.26	13.19 ± 0.96
10	10.55 ± 0.06	2.30 ± 0.15	20.90 ± 1.59	24.21 ± 1.71	17.90 ± 1.27
11	7.64 ± 0.99	2.55 ± 0.07	22.60 ± 0.72	19.53 ± 2.70	14.43 ± 1.99
12	8.24 ± 0.34	2.38 ± 0.12	24.54 ± 1.08	19.62 ± 1.53	14.48 ± 1.12
13	8.87 ± 0.23	3.17 ± 0.25	16.63 ± 0.36	28.08 ± 2.25	20.76 ± 1.67
14	9.96 ± 0.36	3.51 ± 0.08	16.43 ± 0.28	35.01 ± 0.54	25.84 ± 0.41
15	7.61 ± 0.08	2.13 ± 0.08	16.05 ± 0.33	16.20 ± 0.63	11.94 ± 0.50
16	8.41 ± 0.27	2.35 ± 0.04	16.00 ± 0.36	19.71 ± 0.81	14.55 ± 0.58
17	8.98 ± 0.43	2.90 ± 0.02	15.62 ± 0.70	26.01 ± 1.35	19.22 ± 0.89
18	8.29 ± 0.62	3.15 ± 0.15	20.13 ± 0.55	26.19 ± 2.88	19.34 ± 2.13
19	9.83 ± 0.60	2.99 ± 0.21	20.06 ± 0.47	29.43 ± 2.07	21.76 ± 1.51
20	7.18 ± 0.14	2.36 ± 0.07	29.78 ± 1.84	16.92 ± 0.72	12.53 ± 0.52
21	6.12 ± 0.71	3.55 ± 0.01	16.96 ± 0.65	21.69 ± 2.52	16.03 ± 1.82
22	8.80 ± 0.18	3.80 ± 0.05	15.60 ± 0.29	33.48 ± 0.10	24.72 ± 0.67
23	9.87 ± 0.88	4.02 ± 0.07	18.36 ± 0.38	39.69 ± 3.87	29.34 ± 2.86
24	10.13 ± 0.65	3.12 ± 0.01	21.60 ± 0.08	31.59 ± 2.16	23.35 ± 1.55
25	8.81 ± 1.02	3.67 ± 0.17	19.45 ± 1.06	32.49 ± 5.13	23.97 ± 3.77
26	9.11± 0.60	3.53 ± 0.05	19.42 ± 0.60	32.13 ± 1.71	23.73 ± 1.23

27	8.81 ± 1.02	3.02 ± 0.02	22.66 ± 2.16	26.55 ± 0.34	19.62 ± 2.27

The LHV of the fuel gas averaged 8.64 ± 0.44 MJ·Nm^{-3}, with the highest recorded value of 10.55 ± 0.06 MJ·Nm^{-3} in Experiment 10, where TPB bamboo was gasified at 700°C using 13–25 mm particles, a 5-minute residence time, and a 9 g sample mass. The graph analysis indicates that the highest LHV values were obtained when gasifying 9 g of biomass at temperatures of 700°C, 800°C, and 900°C. Particle size played a significant role in these results, as the best-performing conditions involved either intermediate-sized chips (6–13 mm) or the largest tested particles (13–25 mm). The type of feedstock did not show a fundamental impact on LHV values, as both biomass types yielded comparable results. Similarly, gasification time did not exert a major influence, as similar LHV values were recorded across different residence times. Comparing these findings with the literature, Peres (1997) reported LHV values of 9.12 MJ·Nm^{-3} at 700°C, 11.38 MJ·Nm^{-3} at 800°C, and 12.45 MJ·Nm^{-3} at 900°C for sugarcane bagasse gasification. Similarly, Kuo et al. (2014) found LHV values ranging from 4.51 MJ·Nm^{-3} to 7.8 MJ·Nm^{-3} for bamboo gasification, while Wenzel (2013) reported a maximum LHV of 6 MJ·Nm^{-3} for leather waste gasification. These comparisons confirm that bamboo-derived syngas exhibits a competitive energy content, making it a promising feedstock for thermal applications.

The volume of gas generated per kilogram of biomass was another critical parameter. The average gas volume across experiments was 2.61 ± 0.07 m^3·kg^{-1}, with the highest value (4.02 ± 0.07 m^3·kg^{-1}) recorded in Experiment 23, where LB bamboo was gasified at 900°C with 6–13 mm particles, a 3-minute residence time, and a 9 g sample mass. The results confirm that higher temperatures (900°C) significantly enhance gas production, while particle size also plays a crucial role, with the best results obtained using medium (6–13 mm) and large (13–25 mm) chips. However, feedstock type did not show substantial influence, as both biomass sources yielded comparable results. Similarly, gasification time had minimal impact, as high gas volumes were consistently observed across different exposure times. These findings are consistent with previous studies. Kuo et al. (2014) reported gas volumes between 1.2 and 2.4 Nm^3·kg^{-1} for bamboo gasification using a downflow fixed-bed gasifier, while Wenzel (2013) obtained values ranging from 1.75 to 2.6 Nm^3·kg^{-1} in the gasification of leather waste. Peres (1997), studying sugarcane bagasse gasification at 700, 800, and 900°C, found significantly lower gas volumes of 0.36, 0.42, and 0.55 Nm^3·kg^{-1}, respectively.

The energy available in the produced syngas also varied significantly. The average energy yield was 22.77 ± 1.62 MJ·kg⁻¹, with the highest value (39.69 ± 3.87 MJ·kg⁻¹) observed in Experiment 23. Consistent with the previous findings, this result was obtained under the same optimal conditions: 900°C, 6–13 mm particle size, 3-minute residence time, and 9 g biomass mass. Similar to gas volume, energy availability was strongly influenced by temperature and particle size, with intermediate (6–13 mm) and larger chips (13–25 mm) yielding the best results. Biomass type had no significant impact, and gasification time remained a secondary factor. Comparing these results with previous studies, Peres (1997) reported energy yields of 3.5 MJ·kg^{-1} at 700°C, 5.2 MJ·kg^{-1} at 800°C, and 7.3 MJ·kg^{-1} at 900°C for sugarcane bagasse gasification, significantly lower than those obtained in bamboo gasification, reinforcing its potential as a high-energy-density biofuel source.

The thermal conversion yield of bamboo gasification had an average value of 17.53 ± 1.21. The highest yield (29.34 ± 2.86%) was observed in Experiment 23, under optimal conditions of 900°C, a particle size of 6–13 mm, a 3-minute residence time, and a 9 g sample mass. The results confirm that temperature plays a crucial role in maximizing thermal efficiency, with the highest values consistently recorded at 900°C. Particle size also influenced performance, as both intermediate (6–13 mm) and large chips (13–25 mm) yielded superior results. However, biomass type showed no significant impact, as both feedstocks performed similarly. Likewise, gasification time had little effect, as similar thermal yields were observed across different exposure times. These findings align with previous studies, such as Geraldo (2013), who reported thermal conversion yields between 5.4% and 18.6% for castor oil plant residue gasification, and Peres (1997), who obtained yields of 18.9% at 700°C, 27.8% at 800°C, and 39.3% at 900°C for sugarcane bagasse.

The formation of char and ash in bamboo gasification is presented in Figure 3, with an average yield of 19.06 ± 0.81% m/m^{-1} across all experiments. The highest value (24.54 ± 1.08% m/m^{-1}) was recorded in Experiment 12, where TPB bamboo was gasified at 700°C, using <6 mm particles, a 3-minute residence time, and a 9 g sample mass. The results indicate that biomass mass and gasification temperature do not have a decisive impact on coal and ash formation, as the highest yields were observed at 700°C, 800°C, and 900°C, with sample masses of 7 g and 9 g. However, particle size was a determining factor, with the best results obtained using smaller chips (<6 mm), suggesting that finer particles lead to increased residual char. Biomass type (LB or TPB) showed no significant influence, as both performed similarly. Likewise, gasification time had no major impact, since similar coal and ash formation values were recorded across different exposure durations. Similar conclusions

on char formation were obtained by Peres (1997), who reported char formation ranging from 13 % $m.m^{-1}$ to 17 % $m.m^{-1}$ in sugarcane bagasse gasification at 700°C, 800°C, and 900°C.

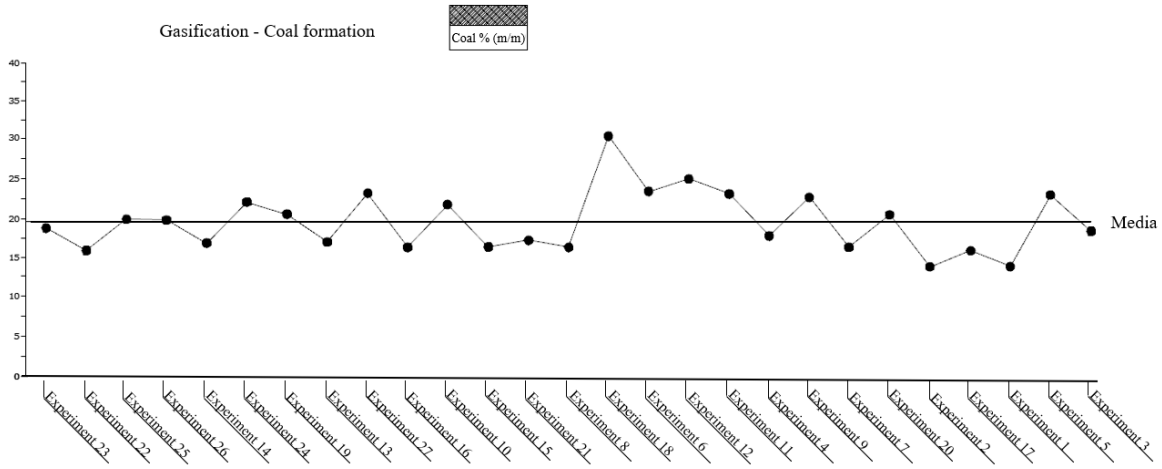


Fig. 3 Char formation in the gasification of LB and TPB bamboo under different experimental conditions.

The potential of bamboo gasification for electric power generation in Brazil is significant, given the vast availability of both cultivated and native bamboo. The estimated 136,000 hectares of cultivated bamboo yield an agricultural productivity of 24 tons per hectare per year, resulting in an annual biomass availability of 3.364 million tons. Considering an energy content of 3,610 MJ per ton of biomass and a thermal conversion efficiency of 24%, this corresponds to an energy potential of 11,783 TJ per year. When applying an electric conversion efficiency of 25%, this energy could generate approximately 818,267 MWh per year.

There is also considerable potential for energy generation when including native bamboo from the Brazilian Amazon, where an estimated 18 million hectares are available, with a productivity of 12 tons per hectare per year. This results in a total annual biomass availability of 216 million tons, translating into 779,760 TJ per year of energy, based on the same 3,610 MJ per ton energy content and 24% thermal conversion efficiency. With an electric transformation yield of 25%, this resource could generate up to 54.15 TWh per year, further demonstrating bamboo's potential as a large-scale renewable energy source.

Conclusions

This study evaluated the feasibility of bamboo (Bambusa vulgaris) biomass gasification as an alternative for sustainable fuel gas production in Brazil. The research analyzed the influence of different operational parameters, including temperature, residence time, biomass type (leafless bamboo and total plant bamboo), and particle size, on energy yield and syngas composition, through a total of 27 experimental conditions.

The results indicated that the optimal operating conditions were achieved with leafless bamboo, using particle sizes between 6 and 13 mm at 900°C and a residence time of 3 minutes (Experiment 23). Under these conditions, gasification produced 4.02 $Nm^3 \cdot kg^{-1}$ of fuel gas, with an energy yield of 39.69 $MJ \cdot kg^{-1}$ and a thermal conversion efficiency of 29.34%. The generated gas predominantly consisted of hydrogen (H_2) and carbon monoxide (CO), highlighting its high energy potential and applicability in thermal and electrical energy generation processes.

A comparative analysis with previous studies demonstrated that bamboo performs competitively compared to other biomass sources, such as sugarcane bagasse and forestry residues, positioning itself as a promising alternative for diversifying Brazil's energy matrix. Bamboo's high productivity and rapid growth rate further reinforce its potential as a sustainable feedstock for thermochemical processes, contributing to reducing dependence on fossil fuels and mitigating the environmental impacts associated with conventional energy generation. Moreover, the findings suggest that bamboo gasification could contribute up to 820 GWh annually to Brazil's energy matrix, offering a low-carbon solution aligned with sustainable energy transition policies. However, further studies are recommended to optimize gasification technology, assess its economic feasibility, and explore its integration into existing energy systems.

Data availability

Data will be made available on request.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Aprianti N, Faizal M, Said M, et al (2023) Gasification kinetic and thermodynamic parameters of fine coal using thermogravimetric analysis. Energy 268:126666. https://doi.org/10.1016/j.energy.2023.126666

Barros Neto B, Scarminio I, Bruns R (2010) Como fazer experimentos, 4 ed. São Paulo: Bookman

Brasil (2011) Lei Federal no 12.484, de 8 de Setembro de 2011. Política Nacional de Incentivo ao Manejo Sustentado e ao Cultivo do Bambu. http://www.planalto.gov.br/ccivil_03/_Ato2011-2014/2011/Lei/L12484.htm. Accessed 21 Mar 2023

Bridgwater A V. (1995) The technical and economic feasibility of biomass gasification for power generation. Fuel 74:631–653. https://doi.org/10.1016/0016-2361(95)00001-L

Chang-hsien Liao, Matthew Summers, Reinhard Seiser, Robert Cattolica RH (2014) Simulation of a pilot-scale dual-fluidized-bed gasifier for biomass. Environ Prog Sustain Energy 33:663–1064. https://doi.org/https://doi.org/10.1002/ep.11945

Chen W, Escalante J, Li L, et al (2025) Catalytic co-gasification optimization of biomass and polyethylene wastes in oxygen-rich environments. Fuel 381:133214. https://doi.org/10.1016/j.fuel.2024.133214

Cheng X, Liu S, Zhou Y, et al (2022) The current status and potential research directions of soil microbial carbon in bamboo forest. Adv Bamboo Sci 1:100005. https://doi.org/10.1016/j.bamboo.2022.100005

Chieng S, Kuan SH (2020) Harnessing bioenergy and high value–added products from rice residues: a review. Biomass Convers Biorefinery. https://doi.org/https://doi.org/10.1007/s13399-020-00891-y

Ciola R (1985) Fundamentos da cromatografia a gás. São Paulo: Edgard Blucher

Demirbas A (2011) Competitive liquid biofuels from biomass. Appl Energy 88:17–28. https://doi.org/10.1016/j.apenergy.2010.07.016

Difs K, Wetterlund E, Trygg L, Söderström M (2010) Biomass gasification opportunities in a district heating system. Biomass and Bioenergy 34:637–651. https://doi.org/10.1016/j.biombioe.2010.01.007

Drumond PM, Wiedman G (2017) Bambus no Brasil: da biologia à tecnologia, 1. ed. CH - Instituto Ciência

Hoje, Rio de Janeiro: ICH

Edenhofer O, Hirth L, Knopf B, et al (2013) On the economics of renewable energy sources. Energy Econ 40:S12–S23. https://doi.org/10.1016/j.eneco.2013.09.015

Energy Institute (2024) 2024 Statistical Review of World Energy

Fabiani M, Greco S, Mentrasti L, et al (2023) Thermal treatment of bamboo with flame: influence on the mechanical characteristics. Adv Bamboo Sci 2:100015. https://doi.org/10.1016/j.bamboo.2023.100015

Fernández-Sarría A, López-Cortés I, Estornell J, et al (2019) Estimating residual biomass of olive tree crops using terrestrial laser scanning. Int J Appl Earth Obs Geoinf 75:163–170. https://doi.org/10.1016/j.jag.2018.10.019

Geraldo BCA (2013) Gaseificação Da Casca E Da Torta Da Mamona Para Produção De Gás Combustível. Universidade Federal de Pernambuco

Gonçalves DS, Matheus D, Costa S, et al (2023) In vitro cloning of Bambusa vulgaris Schrad. ex J. C. Wendl._ Effect of culture systems, sucrose and activated charcoal supplementation. Adv Bamboo Sci 3:100024. https://doi.org/10.1016/j.bamboo.2023.100024

Greencorn MJ, Jackson SD, Hargreaves JSJ, et al (2023) Enhancement of gasification in oxyfuel BECCS cycles employing a direct recycling CO2 utilisation process. Energy Convers Manag 277:116601. https://doi.org/10.1016/j.enconman.2022.116601

Hagge MJ, Bryden KM (2002) Modeling the impact of shrinkage on the pyrolysis of dry biomass. Chem Eng Sci 57:2811–2823. https://doi.org/10.1016/S0009-2509(02)00167-7

Jamir J, Chen W, Mohd W, et al (2025) Prediction construction for biomass and high-density polyethylene co-gasification via statistical method and machine learning ☆. Fuel 391:134828. https://doi.org/10.1016/j.fuel.2025.134828

Junior M, Nogueira B, Chauque S, et al (2025) Biomass and Bioenergy Untreated bamboo biochar as anode material for sustainable lithium ion batteries. Biomass and Bioenergy 193:107511. https://doi.org/10.1016/j.biombioe.2024.107511

Kirkels AF, Verbong GPJ (2011) Biomass gasification : Still promising ? A 30-year global overview. Renew Sustain Energy Rev 15:471–481. https://doi.org/10.1016/j.rser.2010.09.046

Kumar A, Chauhan AS, Bains R, Das P (2021) Rice straw (Oryza sativa L.) biomass conversion to furfural, 5-hydroxymethylfurfural, lignin and bio-char: A comprehensive solution. J Ind Eng Chem 104:286–294. https://doi.org/10.1016/j.jiec.2021.08.025

Kumar R, Chandrashekar N (2014) Fuel properties and combustion characteristics of some promising bamboo species in India. J For Res 25:471–476. https://doi.org/10.1007/s11676-014-0478-6

Kuo PC, Wu W, Chen WH (2014) Gasification performances of raw and torrefied biomass in a downdraft fixed bed gasifier using thermodynamic analysis. Fuel 117:1231–1241. https://doi.org/10.1016/j.fuel.2013.07.125

Lauri P, Havlík P, Kindermann G, et al (2014) Woody biomass energy potential in 2050. Energy Policy 66:19–31. https://doi.org/10.1016/j.enpol.2013.11.033

Leonídia P, Douglas M, Lima R, et al (2025) Exploring the effects of slow pyrolysis temperature and species on the quality of charcoal from Amazonian woody wastes. 240:. https://doi.org/10.1016/j.renene.2024.122257

Letichevsky S, Gontijo LOL, Barbosa MN, et al (2023) 3D conductive monolithic carbons from pyrolyzed bamboo for microfluidic self-heating system. 213:. https://doi.org/10.1016/j.carbon.2023.118214

Li J, Paul MC, Czajka KM (2016) Studies of Ignition Behavior of Biomass Particles in a Down-Fire Reactor for Improving Co-firing Performance. Energy and Fuels 30:5870–5877. https://doi.org/10.1021/acs.energyfuels.6b01065

Lombardo E (2022) An overview of bamboo cultivation in Southern Italy. Adv Bamboo Sci 1:100002. https://doi.org/10.1016/j.bamboo.2022.100002

Londoño X, Clark LG (2002) A Revision of the Brazilian Bamboo Genus Eremocaulon (Poaceae: Bambuseae: Guaduinae). Syst Bot 27:19

Martins AH, Rouboa A, Monteiro E (2023) On the green hydrogen production through gasification processes: A techno-economic approach. J Clean Prod 383:. https://doi.org/10.1016/j.jclepro.2022.135476

Mohammad A, Gahlot P, Moustakas K, et al (2022) Pretreatment methods to enhance solubilization and anaerobic biodegradability of lignocellulosic biomass (wheat straw): Progress and challenges. Fuel 319:123726. https://doi.org/10.1016/j.fuel.2022.123726

Mu Q, Aleem RD, Liu C, et al (2024) Oxygen blown steam gasification of different kinds of lignocellulosic biomass for the production of hydrogen-rich syngas. Renew Energy 232:121132. https://doi.org/10.1016/j.renene.2024.121132

Nguyen HN (2024) Integrated CO2-hydrothermal carbonization and high temperature steam gasification of bamboo feedstock: A comprehensive experimental study. Adv Bamboo Sci 6:100060. https://doi.org/10.1016/j.bamboo.2024.100060

Odega CA, Ayodele OO, Ogutuga SO, et al (2023) Potential application and regeneration of bamboo biochar for wastewater treatment: A review. Adv Bamboo Sci 2:100012. https://doi.org/10.1016/j.bamboo.2022.100012

Parikh J, Channiwala SA, Ghosal GK (2005) A correlation for calculating HHV from proximate analysis of solid fuels. Fuel 84:487–494. https://doi.org/10.1016/j.fuel.2004.10.010

Peres S (1997) Catalytic indirectly heated gasification of bagasse. University of Florida

Presznhuk RA de O (2004) Estudo da viabilidade do filtro de carvão de bambum como pós-tratamento em estação de tratamento de esgoto por zona de raízes: tecnologia ambiental e socialmente adequada. Centro Federal de Educação Tecnológica do Paraná

Qiu Y, Rao S, Zhong L, et al (2024) Biomass and Bioenergy Study on the mechanism of hydrogen production from bamboo gasification in supercritical water by ReaxFF molecular dynamics simulation. Biomass and Bioenergy 191:107472. https://doi.org/10.1016/j.biombioe.2024.107472

Quan C, Zhang J, Tang Z, et al (2023) Investigation on the influence of inherent AAEMs on gasification reactivity of solid digestate char. Fuel 335:127015. https://doi.org/10.1016/j.fuel.2022.127015

Rousset P, Aguiar C, Labbé N, Commandré JM (2011) Enhancing the combustible properties of bamboo by torrefaction. Bioresour Technol 102:8225–8231. https://doi.org/10.1016/j.biortech.2011.05.093

Safarian S, Unnþórsson R, Richter C (2019) A review of biomass gasification modelling. Renew Sustain

Energy Rev 110:378–391. https://doi.org/10.1016/j.rser.2019.05.003

Saghir M, Rehan M, Nizami A-S (2018) Recent Trends in Gasification Based Waste-to-Energy. Gasif Low-grade Feed. https://doi.org/10.5772/intechopen.74487

Sahu GC, Bandyopadhyay S, Foo DCY, et al (2014) Targeting for optimal grid-wide deployment of carbon capture and storage (CCS) technology. Process Saf Environ Prot 92:835–848. https://doi.org/10.1016/j.psep.2013.05.003

Saidur R, Abdelaziz EA, Demirbas A, et al (2011) A review on biomass as a fuel for boilers. Renew Sustain Energy Rev 15:2262–2289. https://doi.org/10.1016/j.rser.2011.02.015

Salem AM, Kumar U, Izaharuddin AN, et al (2018) Advanced Numerical Methods for the Assessment of Integrated Gasification and CHP Generation Technologies. In: De S, Agarwal A, Moholkar V (eds) Coal and Biomass Gasification. Energy, Environment, and Sustainability. Springer, Singapore.

Scarlat N, Blujdea V, Dallemand JF (2011) Assessment of the availability of agricultural and forest residues for bioenergy production in Romania. Biomass and Bioenergy 35:1995–2005. https://doi.org/10.1016/j.biombioe.2011.01.057

Sepe AM, Li J, Paul MC (2016) Assessing biomass steam gasification technologies using a multi-purpose model. Energy Convers Manag 129:216–226. https://doi.org/10.1016/j.enconman.2016.10.018

Siripaiboon C, Sarabhorn P, Areeprasert C, Scala F (2023) Design and simulation of a novel top-lit downdraft gasifier cookstove and performance comparison with a conventional top-lit updraft cookstove. Energy. https://doi.org/10.1016/j.energy.2023.126782

Tanger P, Field JL, Jahn CE, et al (2013) Biomass for thermochemical conversion: Targets and challenges. Front Plant Sci 4:. https://doi.org/10.3389/fpls.2013.00218

Tri Setioputro N, Muchammad, Yohana E, et al (2025) Effect of soaked biomass on gasification temperature performance in an open-downdraft gasifier. Bioresour Technol 415:131651. https://doi.org/10.1016/j.biortech.2024.131651

Van Soest PJ, Robertson JB, Lewis BA (1991) Methods for Dietary Fiber, Neutral Detergent Fiber, and Nonstarch Polysaccharides in Relation to Animal Nutrition. J Dairy Sci 74:3583–3597.

https://doi.org/10.3168/jds.S0022-0302(91)78551-2

Wang X, Chen Q, Zhu H, et al (2023a) In-situ study on structure evolution and gasification reactivity of biomass char with K and Ca catalysts at carbon dioxide atmosphere. Carbon Resour Convers 6:27–33. https://doi.org/10.1016/j.crcon.2022.10.002

Wang Y, Ge Z, Shang F, et al (2023b) Kinetic analysis of CO2 gasification of corn straw. Renew Energy 203:219–227. https://doi.org/10.1016/j.renene.2022.12.074

Wei Z, Li Y, Zhang C, et al (2023) Revealing the mechanism on steam co-gasification of cellulose and polyethylene: A combined ReaxFF and DFT study. Fuel 334:126784. https://doi.org/10.1016/j.fuel.2022.126784

Wenzel BM (2013) Tratamento térmico de resíduos calçadistas: Estudo da gaseificação, tratamento dos gases e aproveitamento das cinzas.). Universidade Federal do Rio Grande do Sul

Xu D, Xiong Y, Ye J, et al (2019) Performances of syngas production and deposited coke regulation during co- gasification of biomass and plastic wastes over Ni / γ-Al 2 O 3 catalyst : Role of biomass to plastic ratio in feedstock. Chem Eng J 123728. https://doi.org/10.1016/j.cej.2019.123728

Yang M, Mousavi SM, Fatehi H, Bai X-S (2023) Numerical simulation ofbiomass gasification in fluidized bed gasifiers. Fuel 337:. https://doi.org/10.1016/j.fuel.2022.127104

Yogalakshmi KN, T PD, Sivashanmugam P, et al (2022) Lignocellulosic biomass-based pyrolysis : A comprehensive review. Chemosphere 286:131824. https://doi.org/10.1016/j.chemosphere.2021.131824

Yu J, Shan S, Zhang Q, et al (2024) Thermal radiation characteristic parameters of biomass mixed feedstock for concentrating solar gasification reaction. 54:

Zanatta FL (2011) Desenvolvimento e avaliação de um gaseificador de biomassa e estudo do potencial de produção de biogás com resíduos agrícolas e da avicultura. Universidade Federal de Viçosa

Zhang K, Chang J, Guan Y, et al (2013) Lignocellulosic biomass gasification technology in China. Renew Energy 49:175–184. https://doi.org/10.1016/j.renene.2012.01.037

Zhou, GuoMo; Jiang, PeiKun; Mo L (2009) Bamboo: a Possible Approach to the Control of Global Warming.

Int J Nonlinear Sci Numer Simul 10:547–550

Zhou G, Meng C, Jiang P, Xu Q (2011) Review of Carbon Fixation in Bamboo Forests in China. Bot Rev 77:262–270. https://doi.org/10.1007/s12229-011-9082-z