



COMPARATIVE ANALYSIS OF DIFFERENT BIOMASS GASIFICATION TECHNOLOGIES FOR SYNGAS PRODUCTION

Kelly Johanna Ortega Jiménez¹, Francisco Rafaél Alarcón Polo², Jorge Mario Mendoza Fandiño³, Jesus David Rhenals⁴, Samuel Ivan Bonilla Gracia^{5*} and Miguel Emigdio Doria Oviedo⁶.

^{1,2,3,4}Department of Mechanical Engineering, Faculty of Engineering, University of Córdoba, Montería, Colombia

^{5,6}Electromechanical Engineering Program, Faculty of Science and Engineering, University of Sinú-Elías Bechara Zainúm, Montería, Colombia

¹<https://orcid.org/0009-0002-2365-8166>, ²<https://orcid.org/0009-0008-1188-3984>, ³<https://orcid.org/0000-0002-5515-5814>

⁴<https://orcid.org/0000-0002-8975-8584>, ⁵<https://orcid.org/0000-0003-4302-163X>, ⁶<https://orcid.org/0000-0003-0337-0851>

E-mail: kortegajimenez57@correo.unicordoba.edu.co, falarconpolo@correo.unicordoba.edu.co, jorge.mendoza@correo.unicordoba.edu.co, jesusrhenalsj@correo.unicordoba.edu.co, [*samuelbonilla@unisinu.edu.co](mailto:samuelbonilla@unisinu.edu.co), migueledoria@unisinu.edu.co.

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ABSTRACT

This research focused on evaluating and comparing biomass gasification technologies such as fluidized bed gasifiers, molten bed gasifiers, entrained bed gasifiers, plasma gasifiers, parallel flow gasifiers, and countercurrent flow gasifiers for the production of synthesis gas, with the aim of identifying which offers the best balance between efficiency, costs, and environmental sustainability. To achieve this, multiple studies and technical articles addressing both the gasification process and the characteristics of syngas and biomass sources were reviewed. The analysis considers key aspects such as operating temperature, biomass conversion to syngas, energy efficiency, operating costs, and minimization of negative environmental impacts. Plasma and molten bath gasifiers operate at higher temperatures, while entrained bed and dual fluidized bed gasifiers stand out for having the highest thermal efficiencies, between 80% and 90%. Plasma gasifiers are the most efficient in terms of generating low levels of CO₂, methane, and solid waste. The choice of gasifier type depends on the budget, production capacity, and characteristics of the biomass.



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I. INTRODUCTION

Colombia is in an energy problem, facing serious difficulties that could lead to a crisis in a short period of time. According to a report by the Unidad Planeación Minero Energética (UPME) in the report Projection of electricity demand and maximum power 2024-2038 [1], shows that the country is facing a potential energy crisis due to a combination of factors, such as dependence on water sources, as approximately 70% of electricity generation comes from hydroelectric plants. The effects of climate change have led to erratic rainfall patterns, which affects hydroelectric generation and increases the vulnerability of the energy system. Energy security is a key factor for the economic and political development of any nation. With continued population growth and technological advances in industry, the demand for energy has increased significantly.

Although renewable energy sources are gaining ground, fossil fuels remain one of the most accessible and reliable options for power generation, currently accounting for more than 80% of the global energy market. However, these fuels are non-renewable and their use increases carbon dioxide (CO₂) emissions, contributing to environmental degradation. Therefore, it is urgent to make the transition from non-renewable energy sources to sustainable alternatives[2]. In this context, the last three decades have seen a resurgence of interest in biomass as an energy source worldwide. Biomass can be understood as organic matter that stores solar energy in its chemical bonds. This energy is released when the bonds between hydrogen, oxygen and carbon atoms are broken through thermochemical conversion processes. The energy released from these materials can be harnessed in a variety of ways. Furthermore, the use of biomass generates no net CO₂ emissions, since the amount released into the atmosphere is equal to the amount absorbed by the plants during their growth.

Synthesis gas is an essential compound used both to generate heat and power and to produce high-value chemicals and liquid fuels, through processes such as Fischer-Tropsch synthesis. In addition, the increasing scarcity of fossil fuels and the negative impact of their carbon emissions have prompted the search for more sustainable alternative sources for the production of synthesis gas [3]. According to other authors, gasification is a thermochemical conversion technology that transforms biomass at temperatures of 650-1200 °C in the presence of a gasifying agent, such as air, oxygen, steam or CO₂. There is renewed interest in biomass gasification as the use of fossil fuels is sought to be decreased; with world oil reserves depleting and global warming a threat, new gasifiers are being developed with potential to produce syngas suitable for synthesis of automotive fuels [4].

The main types of gasifiers for the production of syngas from biomass are: fixed bed, with a simple design and low cost, although with higher production of tars; fluidized bed, efficient and adaptable to heterogeneous biomass; entrained bed, which operates at high temperatures and generates clean syngas; molten bath, which uses liquid media to reduce impurities; and plasma, which decomposes the biomass at the molecular level, achieving a high-purity syngas. Each technology is adapted to different needs and scales of application. The main objective of this work is to study the potential of biomass valorization technologies based on gasification, comparing them with each other and estimating the capacity of their utilization, as well as the economic value in the market of the synthesis gas generated by each of them.

II. MATERIALS AND METHODS

A systematic review of the literature was conducted to examine current research on biomass gasification technologies and syngas production. Peer-reviewed articles and technical reports indexed in recognized scientific databases were selected according to their relevance and methodological quality. The selected studies were analyzed comparatively with emphasis on gasification efficiency and syngas composition, especially hydrogen (H₂) and carbon monoxide (CO) content. The evaluation also considered tar formation, impurity levels, pollutant emissions and economic aspects. This approach allowed the identification of technological trends, key challenges and research gaps in the field. Regarding gasification efficiency, the biomass-to-syngas conversion yields reported in studies were compared, especially those detailing the lower heating value (LHV) of the syngas produced and the thermal efficiency of the gasification processes.

In addition, the quality of the syngas was evaluated, considering parameters such as the composition of the main gases (CO, CO₂, CH₄, H₂), the presence of minor contaminants such as methane and ethanol, since these factors are determining factors for the quality of the syngas and its possible use in industrial processes or energy generation. In relation to pollutant emissions, the levels of pollutant gases emitted by the different technologies, such as carbon dioxide (CO₂), carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO_x) and particulates, were reviewed in order to identify the cleanest technologies in terms of environmental impact. Finally, an evaluation of the cost of the gasification technologies was carried out, analyzing data on initial investment costs (CAPEX) and operating costs (OPEX). These data were compared to understand the economic viability of each technology in terms of its efficiency, the quality of the syngas produced, its environmental impact and economic sustainability. The results obtained were synthesized in comparative graphs, which allowed a clear visualization of the strengths and weaknesses of each technology in relation to the evaluated criteria.

III. RESULTS AND DISCUSSIONS

III.1 REVIEW OF THE LITERATURE

III.1.1 Biomass

Biomass refers to non-fossilized, biodegradable organic materials derived from plants, animals and microorganisms. This includes by-products, residues and wastes from agriculture, forestry and related industries, as well as non-fossilized, biodegradable organic fractions of industrial and municipal wastes [5].

III.1.2. Types of Biomass

The selection of the type of biomass is a key aspect in gasification processes, since its characteristics directly influence the performance and efficiency of the system. Factors such as moisture content, elemental composition, calorific value and amount of ash determine the behavior of the material during the different stages of the process and affect the quality of the syngas obtained.

Moreover, not all biomasses react in the same way. Agricultural, forestry or agro-industrial residues can present significant differences in their structure and composition, which impacts operational stability, tar formation and conversion efficiency. For this reason, proper biomass characterization is essential to define the optimal operating conditions and improve the overall performance of the gasification process.

III.1.2.1 Agricultural residues

Agricultural residues used in gasification include rice husks, wheat straw, corn stalks and sugarcane bagasse. These residues are characterized by their high cellulose and lignin content, as well as low moisture and ash content, which favors an efficient gasification process. This type of biomass is common in agricultural regions and is an economical and abundant option for energy generation [6].

III.1.2.2 Forest Residues

Forest residues, such as wood chips, branches, bark and sawdust, are also common materials for gasification. These residues have high energy density and low moisture content when properly dried. The variability between hardwoods and softwoods influences the performance of the gasification process, due to their differences in composition and density [7].

III.1.2.3 Urban And Organic Waste

Urban and organic wastes, such as food scraps, garden pruning's and municipal waste, offer an alternative source of biomass. These materials tend to have a high moisture content and variable composition, which may require pre-treatment to improve their gasification efficiency. However, they are abundant in urban areas and their use contributes to the reduction of landfill waste [8], [9].

III.1.2.4 Industrial Wastes

Industrial wastes, which include by-products from the pulp and paper industry, biodiesel residues and vegetable oils, have a relatively uniform composition and low moisture content if they are preprocessed. This uniformity allows for greater predictability in the gasification process and facilitates [10].

III.1.2.5 Dedicated Energy Crops

Dedicated energy crops, such as miscanthus, eucalyptus and switchgrass, are grown specifically for their high productivity and energy efficiency. These crops allow control of their composition, which facilitates their use in gasification processes, although they require an investment in land and growing time [11].

III.1.3. Gasification

Gasification is a process by which a solid material (usually coal or biomass) is converted into gas through the reaction with gasifying agents. There are different equipments, agents and tools involved in the gasification process [12].

The main advantage of biomass gasification over other thermochemical conversion technologies stems from the significantly higher temperatures involved, resulting in a higher quality and cleaner syngas due to the sharp removal of unwanted impurities.

III.1.4. Synthesis Gas

Syngas produced by high-temperature gasifiers, typically operating in the range of 1100 to 1300 °C, consists mainly of H_2 and CO, with a limited presence of hydrocarbons, such as CH_4 . On the other hand, syngas generated by moderate temperature gasifiers, typically in the range of 800 to 900 °C, can contain up to 10 % hydrocarbons [13]. In addition, the process produces several minor compounds, including tars, nitrogen and sulfur-based compounds, hydrogen halides and alkali metals. The amounts of these minor components depend on the specific composition of the biomass.

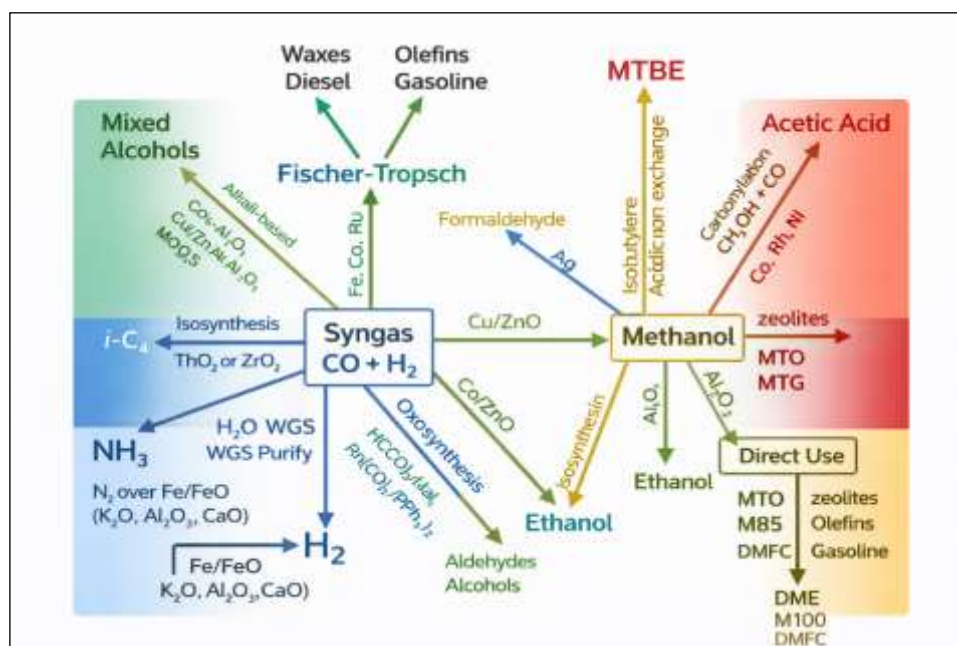


Figure 1: Gasification gas applications.

Source: [14]

III.2 SYNTHESIS GAS PRODUCTION

III.2.1 Fixed Bed Type Gasifier:

It is the oldest technique and the one with the largest number of industrial installations. This type of gasifier has well defined partial combustion, reduction, pyrolysis and drying zones. The oxidizing agent can be air, oxygen and water vapor and is introduced through the lower part of the gasifier and circulates in countercurrent with the solid fuel that is fed through the upper part at relatively low temperatures, since the sensible heat of the gas is used to preheat and dry the fuel; thus high efficiencies are achieved. The solid fuel for this type of gasifier requires prior chopping and screening to avoid feeding too fine particles that can be carried away by the rising gas stream [15].

III.2.1.1 Parallel Flow Gasifier:

A parallel flow gasifier is a type of reactor used for the conversion of biomass or solid fuels into synthesis gas (syngas), through a process known as gasification. In this type of gasifier, the flow of air or oxidizing agent (such as oxygen or steam) is introduced into the reactor parallel to the biomass stream, which generates a direct contact between the two, favoring the thermal treatment of the organic matter. In a parallel flow gasifier, the biomass is fed from the top of the reactor, while the oxidizing agent (such as air or oxygen) is introduced through a parallel duct, usually from the base of the reactor.

As the gas and biomass flow proceeds, the organic material is thermally decomposed, producing gases such as carbon monoxide (CO), hydrogen (H₂), methane (CH₄) and carbon dioxide (CO₂), as well as solid residues, mainly in the form of ash. The main characteristic of the parallel flow gasifier is that the biomass and the oxidizing agent move in opposite or parallel directions within the reactor. This allows good contact between the two flows, which facilitates the gasification process, although it may result in lower conversion efficiency compared to other types of gasifiers [16].

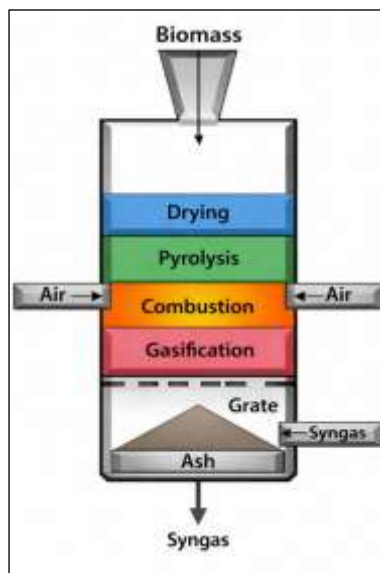


Figure 2: Parallel flow gasifier.

Source: [16]

III.2.1.2 Countercurrent Fixed Bed Gasifier

Here the biomass is fed from the upper part of the reactor and the gasifying agent is fed from the lower part. The processes that take place are: drying, pyrolysis, gasification and combustion. In the combustion of char, CO and CO₂ and a small amount of H₂O are released, these gases are at about 1000 °C temperature, continue to rise through the gasifier and are reduced to CO and H₂, which are cooled down to 750 °C. These gases continue to rise, so that pyrolysis and drying of the solid continues, and eventually leaves the reactor at about 500 °C. As the pyrolysis takes place in the low-temperature zone, the gas obtained in this type of gasification usually contains large amounts of tars and volatile condensable species [17].

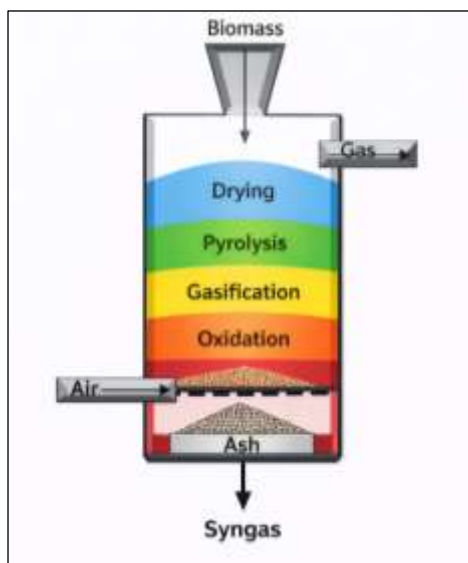


Figure 3: Countercurrent fixed bed gasifier.

Source:[17].

III.2.2 Fluidized Bed Type Gasifier

These gasifiers are of simpler construction than the fixed bed gasifiers. The solid is fed with a finer size than in the fixed bed, and the gasifying agent is injected at the bottom. The reaction takes place with the solid suspended in the gas stream, which facilitates contact between the two phases. The ash is usually extracted from the bottom. The crushed solid is fed laterally into the gasifier, where there is a uniform temperature (for biomass it operates at about 800-900°C). The gasifying agents, which are introduced from the bottom at a high velocity, keep the solid particles in suspension, forming a fluid that behaves like a liquid while the reactions take place [18].

The ash is extracted at the bottom, while the gas usually entrains unburned solid particles that in more advanced gasifiers are usually collected and recirculated to the bed. The conversion of the carbon contained in the biomass usually reaches values close to 100% if the fly ash is re-circulated, which is usually not economical on a small scale. The volume of gas produced per unit volume of the reactor is higher than in fixed-bed gasifiers, which translates into a lower price. The gas composition is very uniform, varying very little with operating conditions due to the good heat and matter transfer conditions provided by the fluidized bed. Since the temperature is uniform throughout the bed, the gases leave the gasifier at a high temperature, which requires optimization.

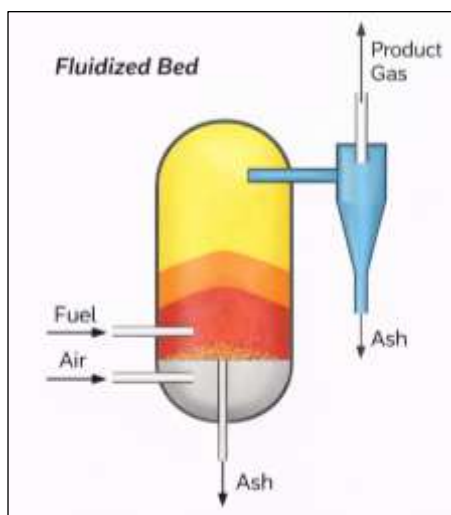


Figure 4: Fluidized bed type gasifier.

Source:[18].

III.2.2.1 Bubbling Fluidized Bed Gasifier:

In a fluidized bed gasifier, the feedstock is mixed and flows with the bed by introducing an oxidizing agent (such as air, oxygen, steam or a combination of these) from the bottom of the reactor. This generates a fluid state in the bed, which expands upward.

The flow rate of the oxidizing agent determines the type of fluidized bed:

- Bubbling fluidized bed (BFB): the flow is moderate, and the particles remain mainly in the reactor as they move in bubbling patterns.
- Circulating fluidized bed (CFB): The flow is so fast that biomass and bed particles are carried out of the reactor along with the gases.

These particles are recovered by cycling and reintroduced into the reactor, forming a continuous cycle.

The fluidized bed has several advantages, such as uniform temperature distribution and greater stability in chemical reactions. In addition, this design is more flexible for fuels with high ash content or other variations in their characteristics [19]. Various configurations of fluidized bed gasifiers are available, including the use of air or oxygen, and can operate at atmospheric pressure or under pressurized conditions. Their design also facilitates scaling up for larger capacity operations [20].

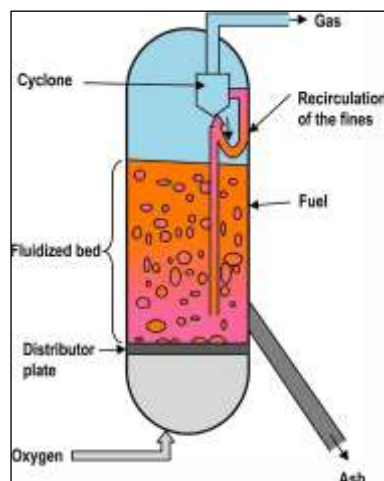


Figure 5: Fluidized bed or bubbling fluidized bed gasifiers.

Source:[20].

III.2.2.2 Dual Fluidized Bed Gasifier:

A dual fluidized bed gasifier is an advanced technology that uses two types of fluidized beds for the conversion of biomass to syngas. The dual fluidized bed gasifier combines the advantages of two types of fluidized beds: the bubbling fluidized bed (BFB) and the circulating fluidized bed (CFB). In the bubbling bed, the gas flow is moderate, which allows the biomass particles to remain inside the reactor, whereas, in the circulating bed, the gas flow is faster and the particles are dragged out of the reactor, being recirculated by a cyclone [21]. One of the main advantages of dual fluidized bed gasifiers is their high energy efficiency. The combination of the two types of fluidized beds allows precise temperature control and uniform heat distribution, which improves the efficiency of biomass-to-syngas conversion. In addition, this technology is flexible in terms of the fuels that can be processed [22].

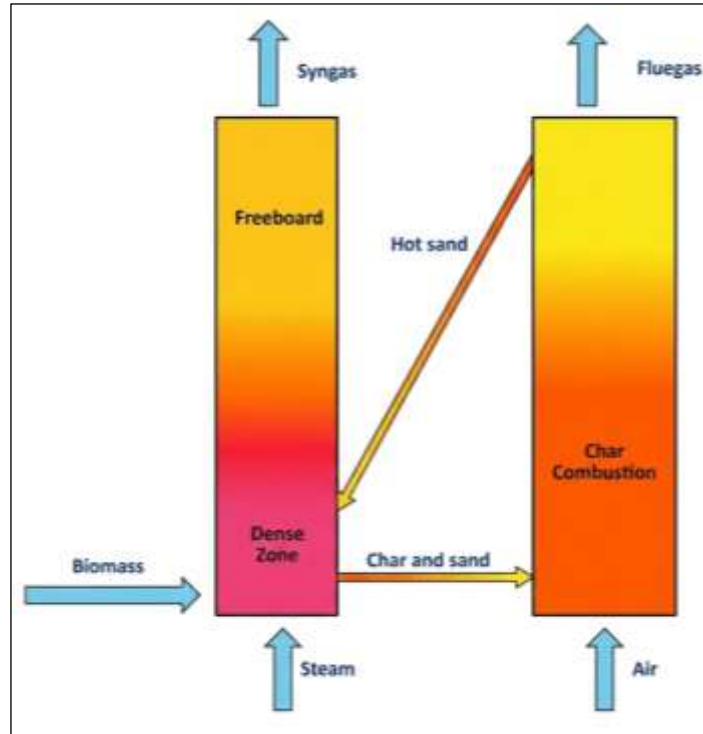


Figure 6: Dual fluidized bed gasifier.
Source:[21].

III.2.3 Molten Bath Gasifier

The molten bath gasifier operates using a bed of molten material, usually composed of molten salts such as potassium or sodium carbonate, which is at high temperatures inside the reactor. In this gasifier, the biomass is fed into the reactor, where it comes into contact with the molten bath at temperatures that can exceed 1000 °C. The molten bath acts as an efficient heat transfer medium, maintaining stable temperatures and providing excellent thermal distribution within the reactor. In addition, the molten bath can help minimize tar formation [23].

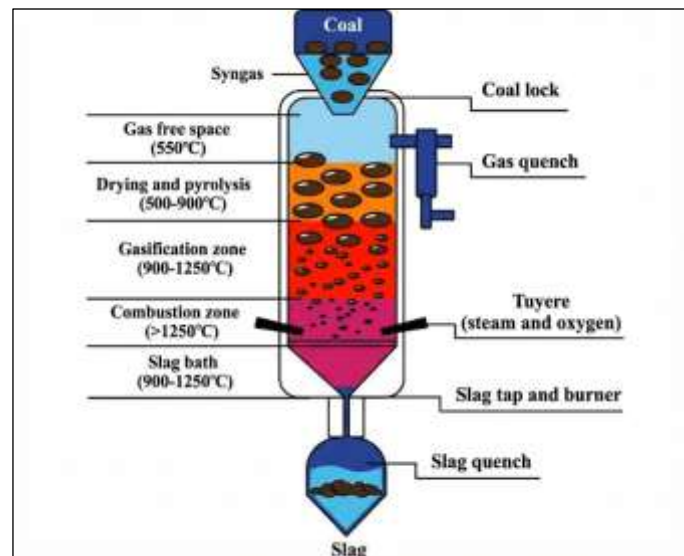


Figure 7: Molten bath gasifier.
Source:[23].

III.2.4 Trailed Bed Gasifier

An entrained bed gasifier (also known as a conveyed bed or upflow gasifier) is a technology used for the conversion of solid fuels, usually finely pulverized biomass or coal, into syngas. This type of gasifier uses a gaseous stream to draw the pulverized fuel through the reactor, resulting in rapid and efficient gasification. Gasification occurs almost instantaneously due to the high temperatures reached inside the reactor, which favors the thermal conversion of biomass into gaseous products [24].

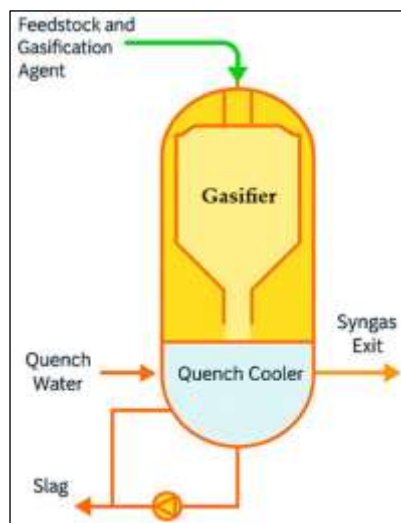


Figure 8: Trailed bed gasifier.
Source: [24]

III.2.5 Plasma Gasifier

This method is considered by some authors as an attractive and environmentally friendly option for waste treatment. In plasma gasification, with the high temperatures that are reached, the organic portion of the biomass is decomposed into its constituent elements and a partially inorganic vitrified slag is left behind [25]. Advantages are the controllability of the process temperature, higher process speeds, smaller reactor volume and especially an optimal composition of the produced gas where the amount of tars is negligible, also inorganic materials are recovered for application in construction. However, it has some notable drawbacks, such as high electricity consumption, the need for resistant materials given the high operating temperature and high investment costs. On the other hand, this process can be understood as an electrical energy storer since it is, in a way, stored in the gas produced.

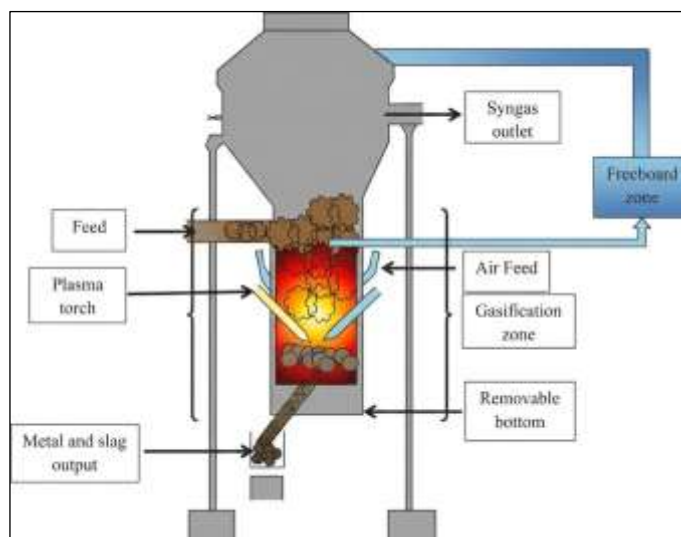


Figure 9: Plasma gasifier.
Source: [25]

III.3 COMPARISON OF THE OPERATING TEMPERATURES OF THE TYPES OF GASIFIERS

In the production of syngas from biomass, the operating temperatures of the gasifiers play a fundamental role in the efficiency of the process and the quality of the gas produced. Gasifiers operating at higher temperatures (plasma and molten bath) offer better biomass conversion while those at lower temperatures are more economical but less efficient. The choice of gasifier will depend on the balance between efficiency, operational costs and the specific requirements of the syngas production process.

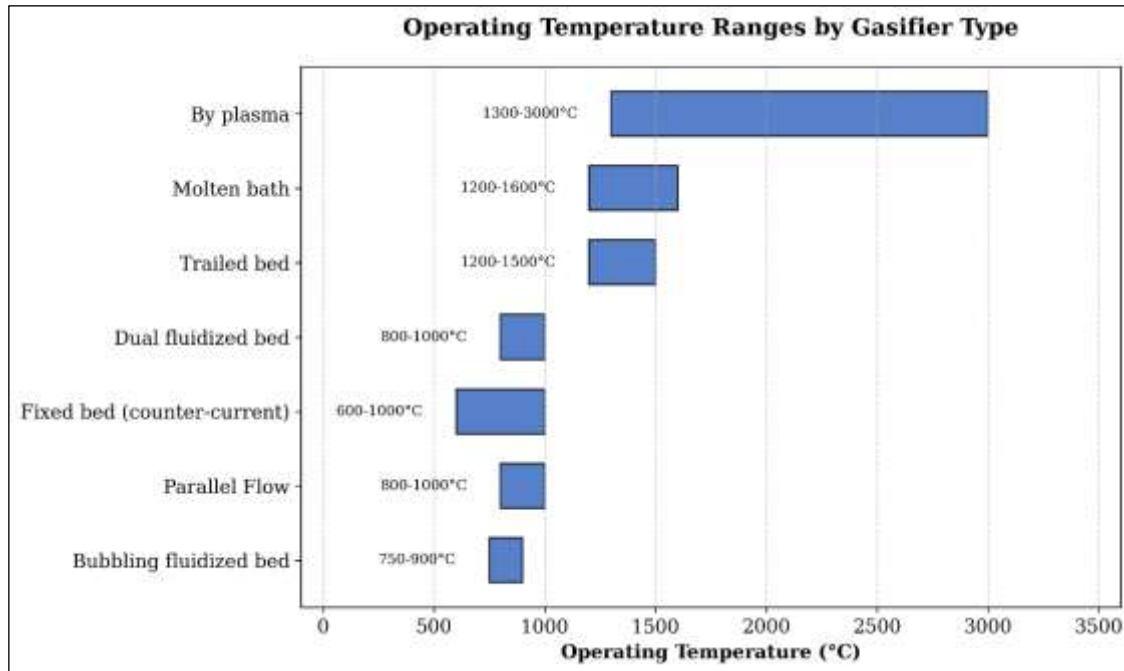


Figure 10: Operating temperatures of the types of gasifiers.
Source: Authors, (2026).

III.4 COMPARISON OF THERMAL EFFICIENCY OF GASIFIER TYPES.

In the production of syngas from biomass, the operating temperatures of the gasifiers play a fundamental role in the efficiency of the process and the quality of the gas produced. Gasifiers operating at higher temperatures (plasma and molten bath) offer better biomass conversion while those at lower temperatures are more economical but less efficient. The choice of gasifier will depend on the balance between efficiency, operational costs and the specific requirements of the syngas production process.

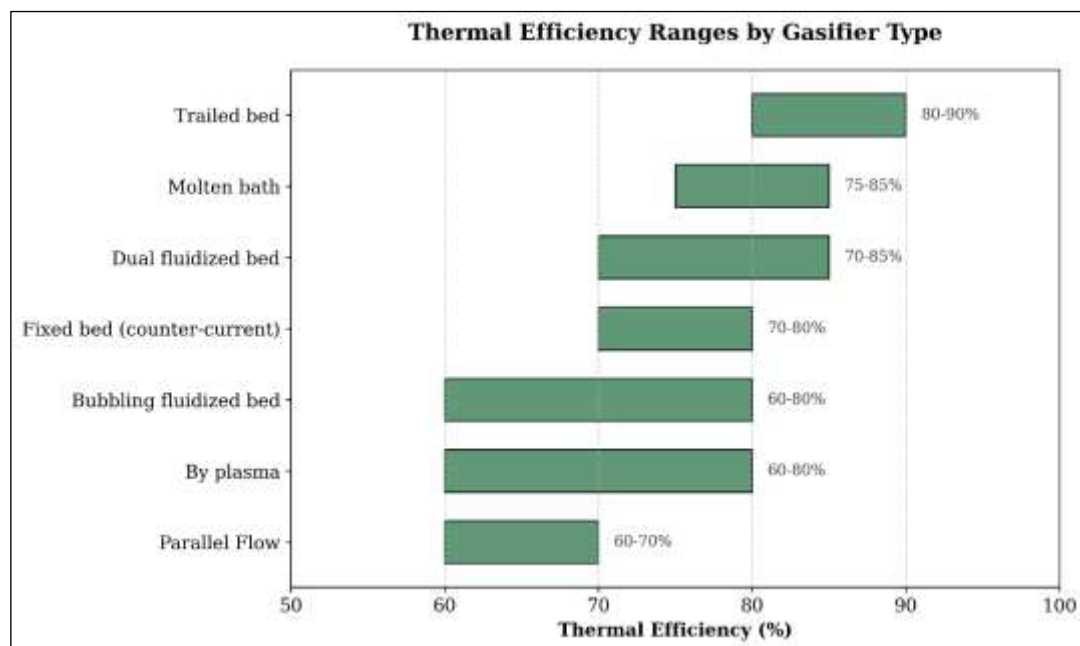


Figure 11: Thermal Efficiency.
Source: Authors, (2026).

III.5 TYPICAL GAS COMPOSITION IN THE SYNGAS.

Trailed bed and dual fluidized bed gasifiers stand out for having the highest thermal efficiencies (between 80% and 90%), which makes them attractive options for efficient syngas production. Molten bath gasifiers have good thermal efficiencies (75% - 85%), although their high operating cost due to high temperatures must be considered. Fixed-bed and bubbling fluidized gasifiers have intermediate thermal efficiencies (60% - 80%), indicating reasonable biomass conversion, but also with higher energy losses. The fixed and bubbling fluidized bed gasifiers have intermediate thermal efficiencies (60% - 80%), indicating reasonable biomass conversion, but also with higher energy losses compared to the more advanced gasifiers.

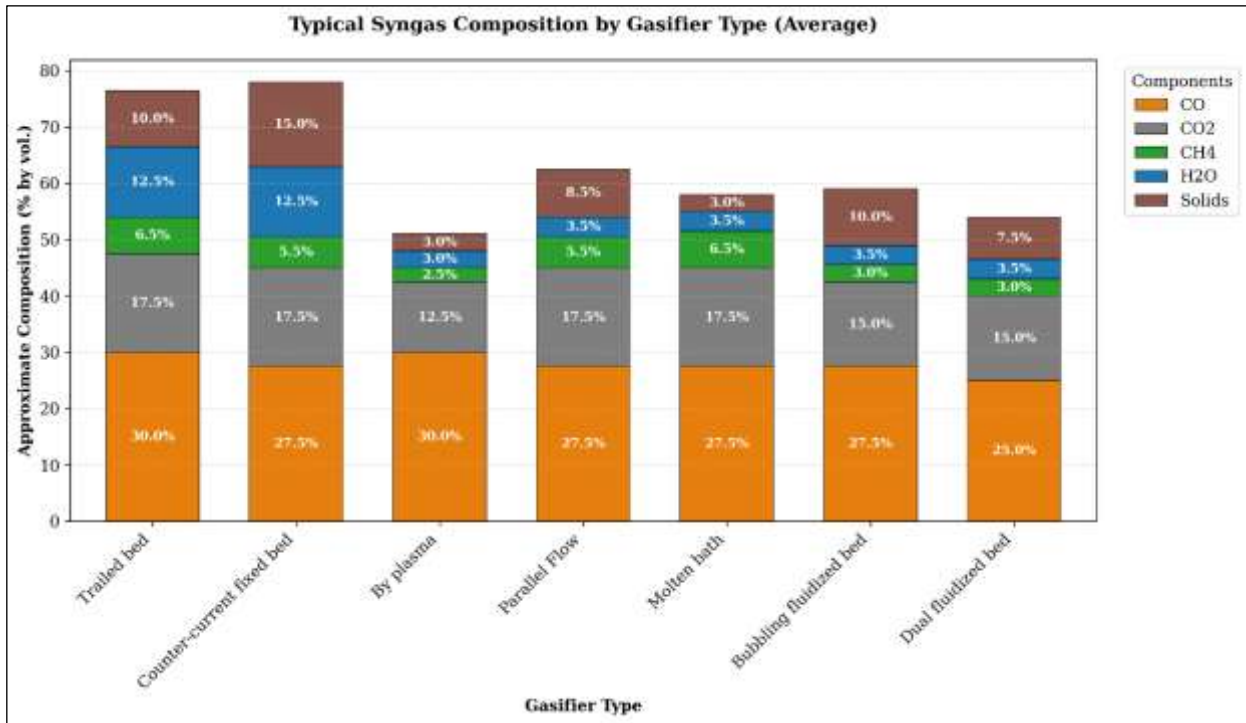


Figure 12: Typical gas composition in the syngas.
Source: Authors, (2026).

III.6 MORE EFFICIENT GASIFIERS

The plasma gasifier is the most efficient in terms of generating low levels of CO₂, methane and solid residues. This type of gasifier also has a low water content, which can be advantageous for certain industrial processes.

III.6.1 Gasifiers With Higher CO And CO₂ Production

Trailed bed and countercurrent fixed bed gasifiers generate higher amounts of CO and CO₂, which could imply lower carbon conversion efficiency and higher environmental impacts if not properly managed.

III.6.2 Solid Waste

The gasifiers with the highest levels of solid waste are the entrained bed, countercurrent fixed bed and bubbling fluidized bed gasifiers, which could generate the need for additional waste management.

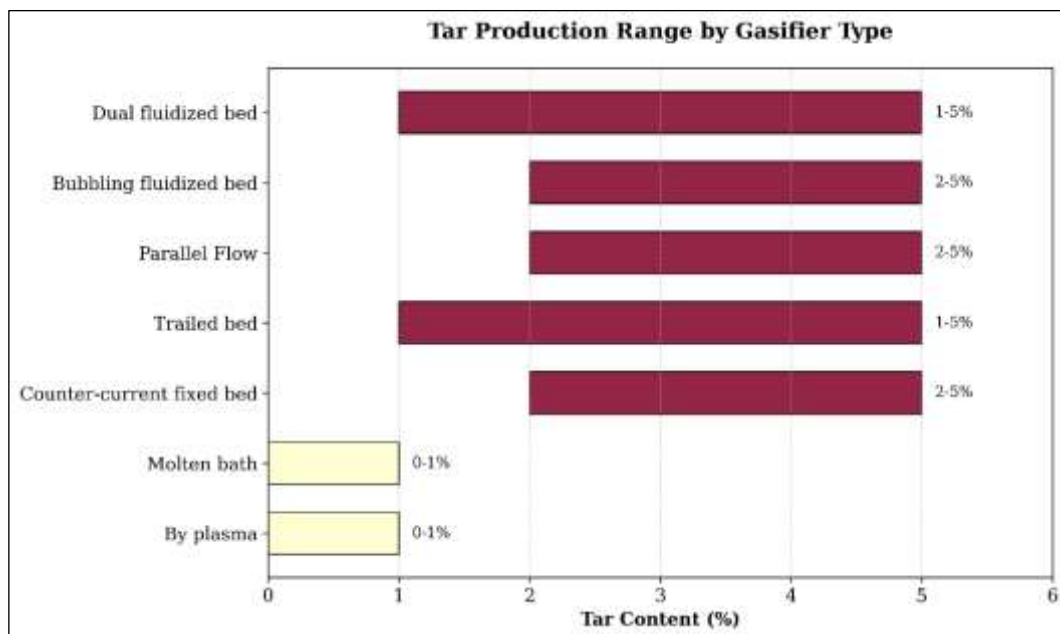


Figure 13: Tar Production Range by Gasifier Type.
Source: Authors, (2026).

Gasifiers using plasma and molten bath technologies are the most efficient in tar reduction, with minimum values of 0%. In contrast, gasifiers with entrained bed, countercurrent fixed bed, parallel flow, bubbling fluidized bed and dual fluidized bed produce higher amounts of tars, with ranges from 1% to 5%. This suggests that these types of gasifiers may require additional tar treatment systems to meet environmental standards.

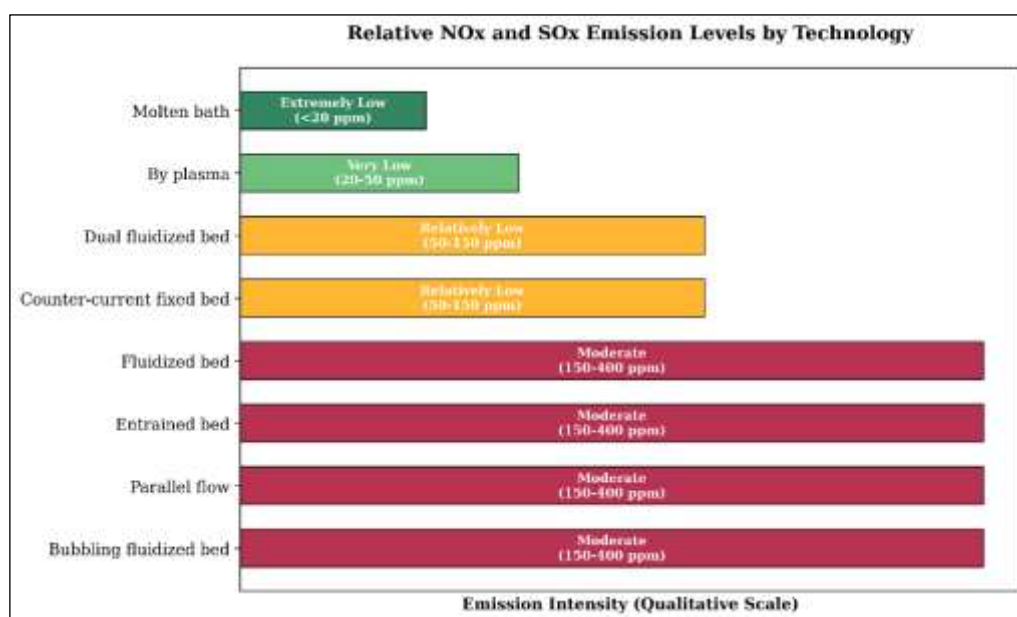


Figure 14: Relative Nox and Sox emission levels by technology.

Source: Authors, (2026).

Control of NOx and SOx emissions depends largely on the type of gasifier used. Gasifiers operating at very high temperatures (such as plasma or molten bath) tend to generate much lower levels of these pollutants. In contrast, gasifiers with fluidized or entrained beds produce moderate emissions, which may require additional emission control systems to meet environmental standards.

III.7 COMPARISON OF INSTALLATION COSTS AND PRODUCTION CAPACITY OF THE DIFFERENT TYPES OF GASIFIERS

The choice of gasifier type depends on budget, production capacity and biomass characteristics. Fluidized bed and entrained bed gasifiers are efficient for large plants, but require high investment. Countercurrent fixed-bed gasifiers are economical for small projects, although less efficient. Plasma and molten bath gasifiers offer great flexibility and efficiency, but are expensive. Parallel flow and bubbling fluidized bed gasifiers are suitable for medium-sized operations, with a balance between cost and performance. The choice depends on the specific needs of the project.

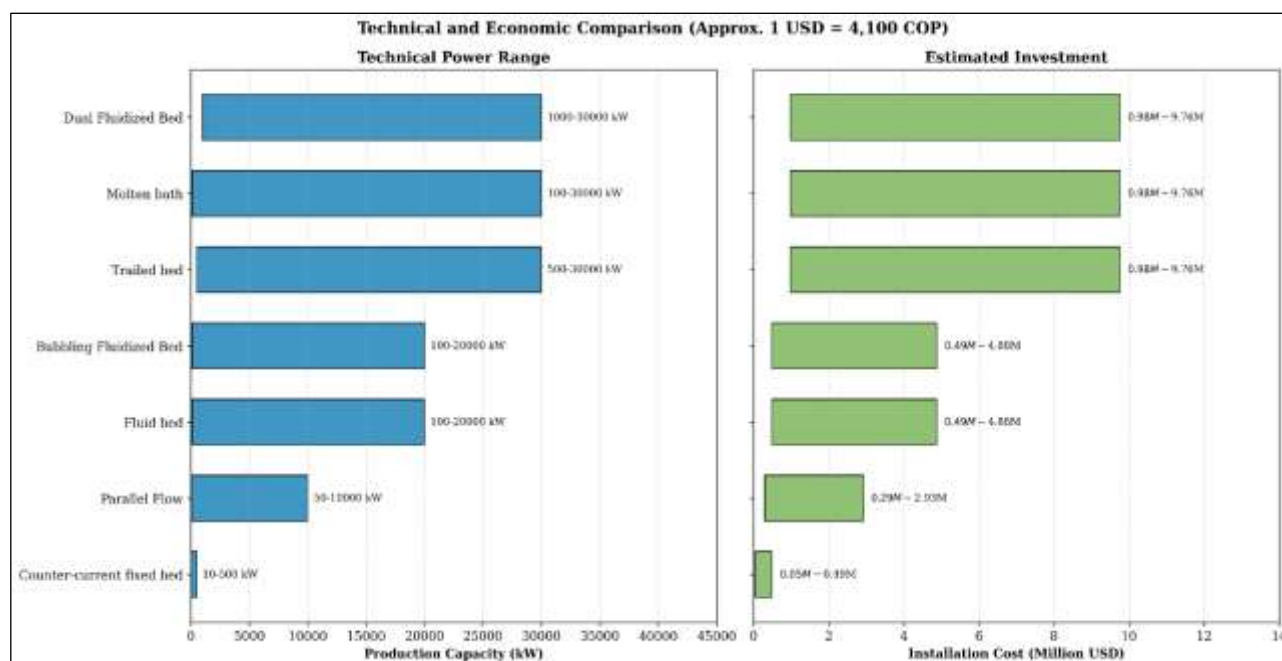


Figure 15: Technical and Economic comparison.

Source: Authors, (2026).

IV. CONCLUSIONS

From the comparison, Plasma and Molten Bath Gasification are better than others as they generate high purity syngas (containing a lot of H₂ or CO), with almost 90% efficiency and less tar slagging and NO_x/SO_x emissions. In contrast, fluidized bed and entrained bed reactors achieve a stable operation balance with attractive efficiencies (70-85%) and uniform gas composition, making them alternative options for industrial applications. But the technology decision should be secured based on how much the project will create and generate. Although high capacity (30,000 kW) systems such as fluidized bed and molten bed systems that require more than \$10 million worth of capital investment are available, fixed bed and parallel flow gasifiers would be the best choice for small and medium sized projects since their installation costs are less than several million dollars. In conclusion, the ideal technology results from a strategic compromise between the quality of the target gas, compliance with environmental regulations, and the economic viability of the initial investment.

V. AUTHOR'S CONTRIBUTION

Conceptualization: Kelly Johanna Ortega Jiménez, Francisco Rafaél Alarcón Polo and Jorge Mario Mendoza Fandiño.

Methodology: Kelly Johanna Ortega Jiménez, Francisco Rafaél Alarcón Polo. Jorge Mario Mendoza Fandiño, Jesus David Rhenals, Samuel Ivan Bonilla Gracia and Miguel Emigdio Doria Oviedo.

Investigation: Kelly Johanna Ortega Jiménez, Francisco Rafaél Alarcón Polo. Jorge Mario Mendoza Fandiño, Jesus David Rhenals, Samuel Ivan Bonilla Gracia and Miguel Emigdio Doria Oviedo.

Discussion of results: Kelly Johanna Ortega Jiménez, Francisco Rafaél Alarcón Polo. Jorge Mario Mendoza Fandiño, Jesus David Rhenals, Samuel Ivan Bonilla Gracia and Miguel Emigdio Doria Oviedo.

Writing – Original Draft: Kelly Johanna Ortega Jiménez, Francisco Rafaél Alarcón Polo. Jorge Mario Mendoza Fandiño, Jesus David Rhenals, Samuel Ivan Bonilla Gracia and Miguel Emigdio Doria Oviedo.

Writing – Review and Editing: Samuel Ivan Bonilla Gracia

Resources: Kelly Johanna Ortega Jiménez, Francisco Rafaél Alarcón Polo. Jorge Mario Mendoza Fandiño, Jesus David Rhenals, Samuel Ivan Bonilla Gracia and Miguel Emigdio Doria Oviedo.

Supervision: Jesus David Rhenals.

Approval of the final text: Miguel Edmigdio Doria.

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