

Review

Biomass Gasification in Downdraft Gasifiers: A Technical Review on Production, Up-Gradation and Application of Synthesis Gas

Pulla Rose Havilah ¹, Amit Kumar Sharma ², Gopalakrishnan Govindasamy ¹, Leonidas Matsakas ³
and Alok Patel ^{3,*}

¹ Department of Chemical Engineering, School of Engineering, University of Petroleum and Energy Studies, Energy Acres Building, Bidholi, Dehradun 248007, India; rosehavilah@ddn.upes.ac.in (P.R.H.); gopalakrishnan@ddn.upes.ac.in (G.G.)

² Department of Chemistry, Centre for Alternate and Renewable Energy Research, R & D, University of Petroleum and Energy Studies (UPES), Energy Acres Building, Bidholi, Dehradun 248007, India; amit.orgchemistry@gmail.com

³ Biochemical Process Engineering, Division of Chemical Engineering, Department of Civil, Environmental and Natural Resources Engineering, Luleå University of Technology, 971 87 Luleå, Sweden; leonidas.matsakas@ltu.se

* Correspondence: alok.kumar.patel@ltu.se; Tel.: +46-(0)920-491570

Abstract: Rapid climate change and forecasted damage from fossil fuel combustion, forced researchers to investigate renewable and clean energy sources for the sustainable development of societies throughout the world. Biomass-based energy is one of the most important renewable energy sources for meeting daily energy needs, which are gaining in popularity daily. Gasification-based bioenergy production is an effective way to replace fossil fuels and reduce CO₂ emissions. Even though biomass gasification has been studied extensively, there is still much opportunity for improvement in terms of high-quality syngas generation (high H₂/CO ratio) and reduced tar formation. Furthermore, the presence of tar has a considerable impact on syngas quality. Downdraft gasifiers have recently shown a significant potential for producing high-quality syngas with lower tar concentrations. This article presents a comprehensive review on the advancement in biomass downdraft gasification technologies for high-quality synthesis gas. In addition, factors affecting syngas production and composition e.g., equivalency ratio, temperature, particle size, and gasification medium on synthesis gas generation are also comprehensively studied. The up-gradation and various applications of synthesis gas are also discussed in brief in this review article.

Keywords: downdraft gasification; biomass; synthesis gas; biochar



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1. Introduction

Global energy demand has been growing steadily for several decades as a result of rapid industrialisation and improved living standards around the world [1]. Extensive use of fossil fuels results in serious problems of ozone depletion, and global warming by emitting poisonous pollutants and greenhouse gases into the environment, especially CO₂ [2,3]. To bridge the gap of growing demand for energy, maintain supply security, and address the problems of adverse environmental consequences caused by fossil fuels, researchers are diverting focus to clean and renewable energy sources. Renewable energy is energy that can be naturally renewed and is derived from natural resources. Solar, wind, marine energy, bioenergy and geothermal energy are the most common renewable energy technologies [4–7]. Among them, biomass is getting more attention as a clean and renewable energy source with more potential.

Biomass has been the primary source of energy for humans since the discovery of fire thousands of years ago, and it continues to contribute more than 10% of the global energy

supply and stands as the world's fourth-largest source of energy today [8]. Furthermore, biomass is still the main source of energy for heating and cooking in rural agricultural areas as it is easily available everywhere. Currently, bioenergy contributes to 14% of the total energy supply, which is the largest renewable energy source [1].

As illustrated in Figure 1 [9], biomass can be classified according to the biological matter from which it is derived. It is divided into three main categories: natural biomass, waste bio-mass, and energetic crops. The residual biomass comprises agricultural, forestry, industrial and urban solid wastes. Bagasse, cotton stalks, rice husks, soya husks, sawdust, de-oiled cakes, coconut shells, coffee waste, groundnut shells, neem, and jute waste are some of the main biomass materials utilized for power generation [10]. Lignocellulose biomass is an abundant non-edible substance consisting mostly of agricultural and forest waste such as wood chips and rice straw. It is mainly composed of cellulose (9–80%), hemicellulose (10–50%), and lignin (5–35%) with trace amounts of lipid, protein and ash [11].

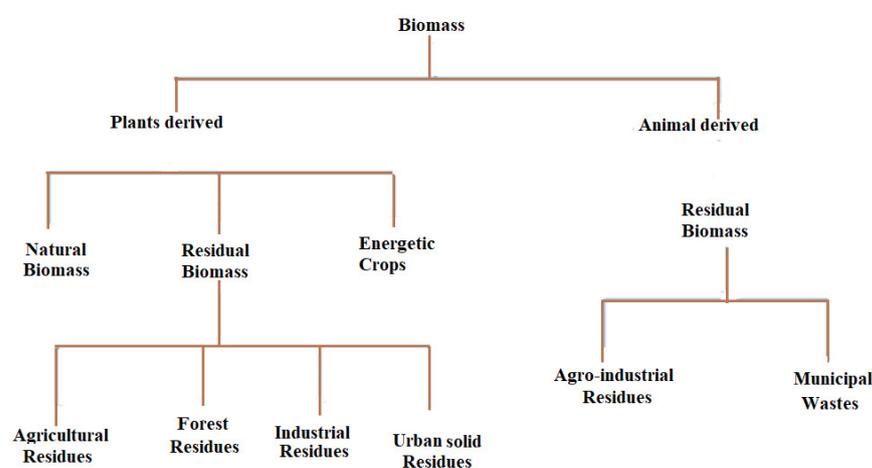


Figure 1. Classification of biomass-based on feedstock origin for mixed biomass pelleting. Adapted with permission from [9]. Copyright 2020, Elsevier.

Thermochemical and biochemical conversions are the most common methods which can be employed to convert biomass into transportation fuels, and high-value compounds [8,12–14] as shown in Figure 2. Biochemical techniques, primary fermentation, aerobic and anaerobic digestion, and enzymatic processes, including a wide range of chemical reactions catalysed inside microorganisms as whole-cell biocatalysts and/or enzymes can convert fermentable material to products. On the other hand, thermochemical methods involve direct combustion, gasification, pyrolysis and liquefaction, where biomass is converted into gas, liquid or solid fuels depending upon the oxygen supply and temperature [12,13,15,16]. Thermochemical conversion is considered more efficient than biochemical due to its high conversion efficiency and short residence time [17]. Pyrolysis is the thermal decomposition of biomass into non-condensable gases, condensable liquids (bio-oil) and a solid residual coproduct, biochar in an inert environment i.e., in the absence of oxygen at temperatures, 350–600 °C [12]. The problem with this method is that substantial upgrading is required for the use of bio-oils as transportation fuels [18]. Liquefaction is a thermal process that transforms biomass into liquid fuels at low temperatures between 250 and 350 °C and high pressures between 10 and 20 MPa. The disadvantages of this approach include its complex reactor system and economic feasibility [19].

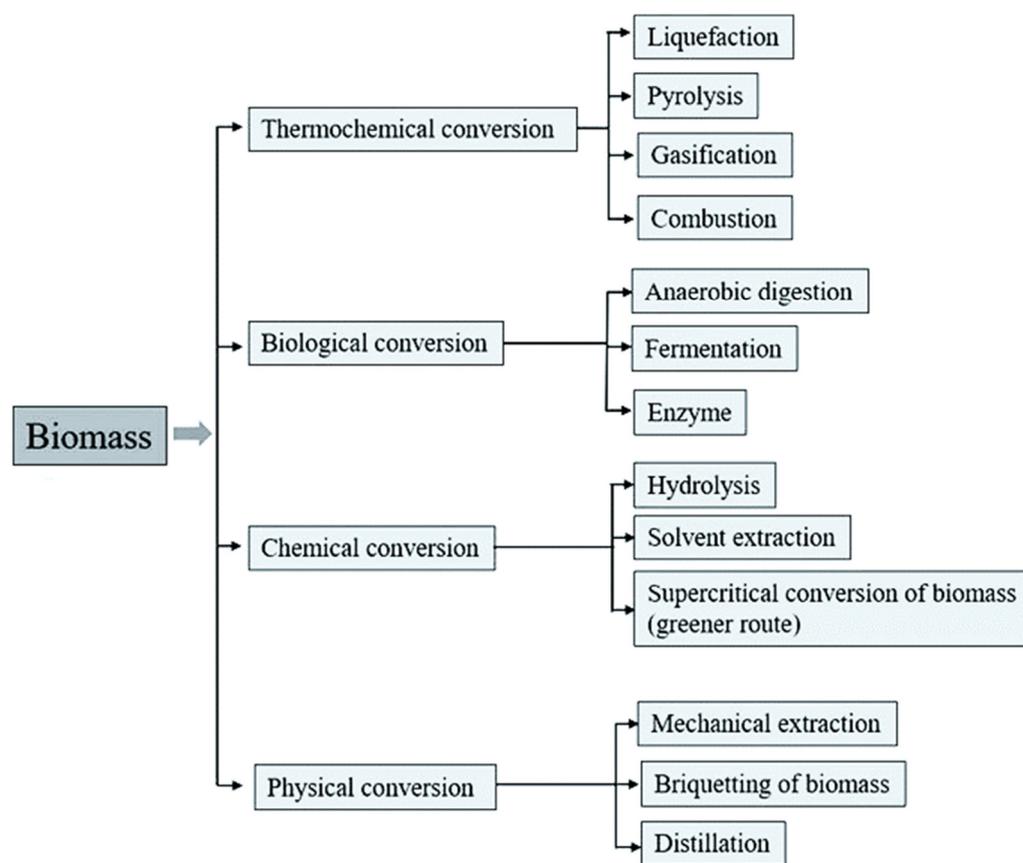


Figure 2. Thermochemical and biochemical methods for biomass conversion [8,20].

Gasification is a highly developed technique that operates at temperatures ranging from 600 to 1500 °C and pressures ranging from atmospheric pressure to 80 bar in the presence of a gasification agent (air, steam, O₂ or CO₂). It is the most efficient way to produce synthesis gas (CO + H₂), with additional components such as CH₄ and CO₂. Light hydrocarbons like ethane and propane, as well as heavier hydrocarbons like tar, are also present in the gas produced [21]. Synthesis gas is further used to make diesel and gasoline grade hydrocarbons, methanol, and ammonia, as well as to generate power and heat [22]. The gasification process is also a good source of green hydrogen production since it offers high overall system efficiency, a quick process, and more choices of integration with other power generation systems. The high hydrogen output, cheap feedstock cost, and environmentally beneficial products also draw attention [23]. A developing country like India also started to focus on the implementation of programmes for biomass gasification for green and clean energy production. According to the Ministry of New and Renewable Energy (MNRE) annual report, as of October 2018, the country has an estimated total biomass gasification installation capacity of 9.54 GW off grid connected bio-power, with a target of 10 GW bio-power by 2022 [24].

Fixed bed gasifiers are the most studied and suitable reactors for biomass gasification due to their simple operation and easy construction. These reactors can be classified into three categories i.e., updraft, downdraft, and cross draft gasifiers. Among them, downdraft gasifiers are getting more popular due to their lower tar content and high-quality syngas. Chaves et al., [25] built a prototype power plant utilizing a downdraft gasifier and observed 2.5 Nm³ kg⁻¹ gas output with a consumption of 5.6 kg/h wood. Ariffin et al. [26] performed gasification of oil palm kernel shells using a medium-scale downdraft gasifier having a capacity of 500 kg and a feed consumption rate of 177 kg/h. The experimental results showed that the cold gas efficiency of the process was found to be 51% at 681 °C with a calorific value (4.45–4.89 MJ/Nm³) ideal for gas engine applications. They examined how

temperature played a key role to improve gasification efficiency. Christus et al. [27] carried out experiments with blends of rubber seed shell and coconut shell on a 50 kW_{th} downdraft gasifier, available in rural parts of South India. They obtained the best performance of the reactor at an equivalence ratio of 0.2. Kallis et al. [28] investigated a 50-kWh pilot downdraft gasifier with an equivalence ratio variation of 0.2–0.3 and found that the heat distribution and resulting temperature distributions had a significant impact on the quality and quantity of the generated gas. According to the study, higher temperatures combined with better heat dispersion resulted in an increase in syngas quantity. Bridge and fuel channelling are common problems in gasifiers. The development of topless or open-top gasifiers has allowed for more efficient fuel feeding. There have only been limited review studies on stratified gasifiers published [29,30]. Mukunda et al. [31] devised a vertical tubular reactor with an open top and a water seal at the bottom for an open-top core gasifier. The reactor's upper portion was made of stainless steel, and it was encircled by an annular jacket. Similarly, an open core, throatless downdraft gasifier reactor with two concentric cylinders was also designed by Ambani and Dafda [31]. The outside cylinder serves as a heat exchanger, while the inner cylinder serves as a reactor. Dasappa et al. [31] developed a mild steel open top downdraft reburn reactor with a ceramic inner liner. Air nozzles were installed throughout the combustion zone, distributing air uniformly over the section by positioning the nozzles at varying heights, promoting high residence time for gases and therefore reducing tar. Wander et al. [32] developed an open-top stratified gasifier with internal gas circulation where a portion of the gas generated was burnt to boost the temperature of the gasification process. The gasifier was used in sawdust gasification of 12 kg/h with a moisture content of 9–11%. They found that the circulation of the internal gases resulted in improved gasification efficiency. Barrio et al. [33] gasified wood pellets at a feed rate of 5 kg/h using a 30 kW stratified downdraft gasifier. The equivalence ratio varied from 0.3–0.45 depending on the air intake. The gasifier generated 12 Nm³/h of gas with a calorific value of 5 MJ/Nm³ and a CO and H₂ concentration of 20%. However, many studies were carried out on downdraft gasification with wood [34], corn straw [35], coconut shell [27], sawdust and wood chips [36], cashew nutshell [37], agricultural and forest residues [38], coir pith [39] and date palm [40] etc., via downdraft gasification of biomass. There is lack of literature reviews on advanced gasification technologies.

Ma et al. 2012 provided an overview of the thermochemical transformation of biomass to produce biofuels, as well as recent breakthroughs and enhancements enabled by tailoring toward the synthesis of gas components. They also discussed the impact of the integration of hydrolysis and gasification for the complete transformation of lignocellulosic biomass [41].

Martínez et al., 2012 reviewed different biomass downdraft reactors for small-scale heat and power generation. They also reviewed the impacts of molecule size, the concentration of biomass feedstock, and the equivalence ratio on the nature of the synthetic gas [42]. Buragohain et al., 2010, mentioned the technical and economic problems related to decentralized power generation utilizing biomass gasification from an Indian perspective [43]. Shahabuddin et al. discussed the benefits and drawbacks of hydrogen production from biomass and municipal solid waste by gasification [44].

The majority of the investigations in the aforementioned review papers were mainly focused on synthesis gas production and characterization. However, there is limited research on improvements to the complete spectrum of production technology, as well as the enrichment and utilization of synthesis gas via biomass downdraft gasification. Therefore, the present review focuses on examining the advancement in production technology, upgrading, and usage of synthesis gas generated from biomass downdraft gasification.

2. Production Aspects of Downdraft Gasification of Biomass

As the name implies, in a downdraft gasifier, air interacts with solid biomass fuel in a downward direction, causing wastes and gases to flow in a co-current direction, therefore these gasifiers are also known as co-current gasifiers. The products obtained from both the

pyrolysis and drying zones due to decomposition are forced to travel through the oxidation zone where thermal cracking of volatile components takes place and results in lower tar content and improved fuel gas quality. Before it reaches the char, air interacts with the pyrolyzing biomass, speeding up the flame and keeping the pyrolysis process going. The gases obtained in the absence of oxygen after the pyrolysis zone are CO₂, H₂O, CO, and H₂, which are referred to as flaming gases. The gases obtained during downdraft gasification in flame pyrolysis are owing to the process itself consuming 99% of the tar, resulting in low particle and tar concentration in the gas, making it suitable for small-scale power generation applications [45].

2.1. Recent Advances and Limitations in Downdraft Biomass Gasification

A typical gasification process consists of four stages: (1) Drying, (2) Pyrolysis, (3) Partial combustion of gases, vapours and char and (4) Reduction of the combustion products [46] which involves a large number of complex chemical reactions namely pyrolysis, partial oxidation, gasification of char, conversion of tars/hydrocarbons and water gas shift reactions. The chemical reactions of biomass gasification are shown below in Table 1. These reactions are strongly influenced by fuel characteristics and process variables such as gasifying agent, gasification temperature and pressure, bed material, and biomass feedstock, all of which are critical for the selection, design, and operation of a given gasifier system [8,47].

Gasifiers are grouped into three categories based on the gas-solid contacting method: fixed bed (updraft and downdraft), fluidized bed, entrained flow, rotary kiln, and plasma gasification [48]. Dense phase reactors comprise fixed bed gasifiers, though lean phase reactors include fluidized bed gasifiers of two kinds: bubbling fluidized bed gasifiers and circulating bed gasifiers and entrained flow gasifiers. Fixed bed gasifiers are a simple and well-proven reactor with a low expenditure cost, but fluidized bed reactors have a high capital expenditure and have only been demonstrated with coal. Furthermore, the entrained flow gasifier is difficult to manufacture [15]. The schematic of various gasifiers is shown in Figure 3. Downdraft gasifiers are primarily divided into two types: (i) Imbert gasifiers (throated or closed-top gasifiers) and (ii) Stratified gasifiers (throatless or open-core gasifiers). Because of the complexity of the Imbert design, the downdraft gasifier models are mostly defined as stratified. The throated gasifiers do not allow for uniform dispersion of flow and temperature in the restricted area, hence are not ideal for scaling up to greater quantities [49].

Table 1. Chemical Reactions occurring during gasification [50,51].

Reaction Type	Reaction	Reaction Heat kJ/mol	Equation Number
Drying : Moist feedstock	+ Heat → Dry feedstock + H ₂ O		(1)
Pyrolysis :	Carbon + Heat → Volatiles + char		(2)
Solid-gas reactions (Heterogeneous Reactions)			
Combustion	C + O ₂ → CO ₂	−394	(3)
Water-gas	C + H ₂ O → CO + H ₂	131	(4)
Boudouard	C + CO ₂ → 2CO	173	(5)
Hydrogasification	C + 2H ₂ → CH ₄	−75	(6)
Gas-gas reactions (Homogeneous Reactions)			
Water gas shift reaction	CO + H ₂ O → CO ₂ + H ₂	−41	(7)
Methanation reactions	CH ₄ + H ₂ O → CO + 3H ₂	206	(8)

Wander et al. [32], for example, demonstrated the design of a 12 kg/h downdraft gasifier for sawmill dust gasification. Susastriawan et al. [52] did a comparative study of the gasification performance of rice husk, sawdust, and their combination in a downdraft fixed-bed gasifier. They investigated the gasification features (reactor temperature profile,

fuel consumption rate, producer gas composition, and gasifier efficiency). Singla et al. [53] gasified rice straw briquettes at four diverse air flow rates and discovered that the heating value of producer gas was decreased at higher airflow rates. Pal [54] investigated the gasification behaviour of cotton stalk biomass in a downdraft gasifier and discovered that with raising the gas flow rate the gasifier efficiency increased. To improve the utilisation of biomass gasification, advanced technologies that optimise syngas yield, improve gas quality, raise gas purity, improve overall process efficiency, and increase economic suitability by lowering total production costs are needed. The UNIQUE gasifier idea demonstrates process integration by combining catalytic filtration, biomass gasification, gas cleaning, and conditioning in a single reactor unit. As a result, the simplified system minimizes thermal losses, equipment, and plant space while attaining excellent thermal efficiency throughout the conversion process. This system allows for the conversion of tar, the removal of trace components, and the provision of high purity syngas appropriate for power production on a small to medium scale, hence increasing overall economic income [51]. Pyrolysis and gasification are separated and integrated into single controlled phases in new enhanced multi-stage gasification ideas. As a consequence, high process efficiencies and low tar content syngas may be obtained. Combining numerous reactors expands the intricacy of the cycle [55]. Multistage necessitates a larger scale and economic feasibility [56]. On the other hand, concepts that combine gasification with a combustion stage aim to improve the overall process capability by combining unconverted char burning for more heat production, or converting tar by partial combustion to generate a product gas with a lower tar concentration [51]. New gasification techniques, such as plasma and supercritical water gasification, provide interesting benefits for specific types of biomasses [8]. For the small-scale industry, there has been more of an era of consolidation, as business administrators have adopted some gasifier advancements and internally developed approaches to improve product quality, reliability, and expense. More importantly, small-scale gasifiers have gained attraction due to steady operations and excellent performance [56].

Bottlenecks in Downdraft Gasification of Biomass

Regardless of broad study, researchers have sought to find the cause of the absence of improvement of biomass gasification for syngas production. Biomass gasification has not yet reached maturity, posing considerable financial risks, and development has been hampered due to the complicated technology [57].

The following are some of the major scientific issues connected with downdraft gasification for biomass thermochemical conversion:

- Expense of collecting and delivering biomass to an energy conversion facility.
- Removal of the impurities such as tar in the gas stream.
- Bridging and scaling of ash in the reactor reduces the gasifier's efficiency and damages the reactor's components.
- High cost of optional, or assistant, hardware to produce clean, generally toxin-free gas.
- Economic and other non-technical hurdles like social inadaptability, inadequate government policies and lack of market float when competing with global energy markets.
- Conversion of biomass into fuel gas of suitable product composition.
- Handling other streams generated in gasification.
- Reactor design for effective gasification of biomass.

A small-scale (1–10 MW) power plant can help to solve technological issues [58]. SCWG (supercritical water gasification) of biomass, according to Hosseini and Wahid [59], is a cost-effective thermochemical technique for hydrogen generation which promotes lower char and tar formation. Meng et al. [60] looked at a pilot size fixed bed gasifier and discovered that a low ER (0.30) caused inefficient combustion, which resulted in more tar being produced. Higher ER, on the other hand, helps to lower tar content and enhance carbon conversion efficiency. The application of magnesite as bed material, according to Siedlecki and de Jong [61], enhanced H₂ concentration in the produced gas. It also decreases the amount of tar in the produced gas to under 2 gm⁻³. Anis et al. [62] discovered that

burning biomass at high temperatures lowers the quantity of tar in the resulting gas. The primary barriers to cost-effective and practical applications are ash-related issues such as sintering, agglomeration, deposition, erosion, and corrosion. To generate electricity commercially, gasification technology combined with a catalytic resulted in tar reduction and leads to lower ash pollution [63]. The two primary pretreatments utilized to lessen ash-related issues are leaching and fractionation. The effectiveness of water leaching in removing inorganic elements was determined by the biomass feedstocks used. Mechanical fractionation can reduce ash in biomass by up to 50%, but the left-over ash still creates ash-related problems at high temperatures [64,65]. Cummer and Brown [66] worked on auxiliary systems, on both the upstream and downstream sides of the entire gasification process. As per previous study [57], innovation designers and government laws assume a basic part in the marketing and commercialization of technologies for the substitution of limited energy supplies. Some techniques from technology developers, such as overall cost minimization, process ease, automation, and so on, can be used to commercialize the technology. Furthermore, policymakers and governmental organizations can take beneficial actions such as giving subsidies for technology implementation, credit facilities, and infrastructure to users [67]. Local governments must provide efficient administration and rigorous monitoring in order to improve any country's bioenergy industry. Efforts to educate technology partners and stakeholders on the uses, applications, and overall expected benefits of gasifiers are also insignificant. To minimize such failures, a sample plan for monitoring biogas consumption in diverse locations on a regular basis might be developed.

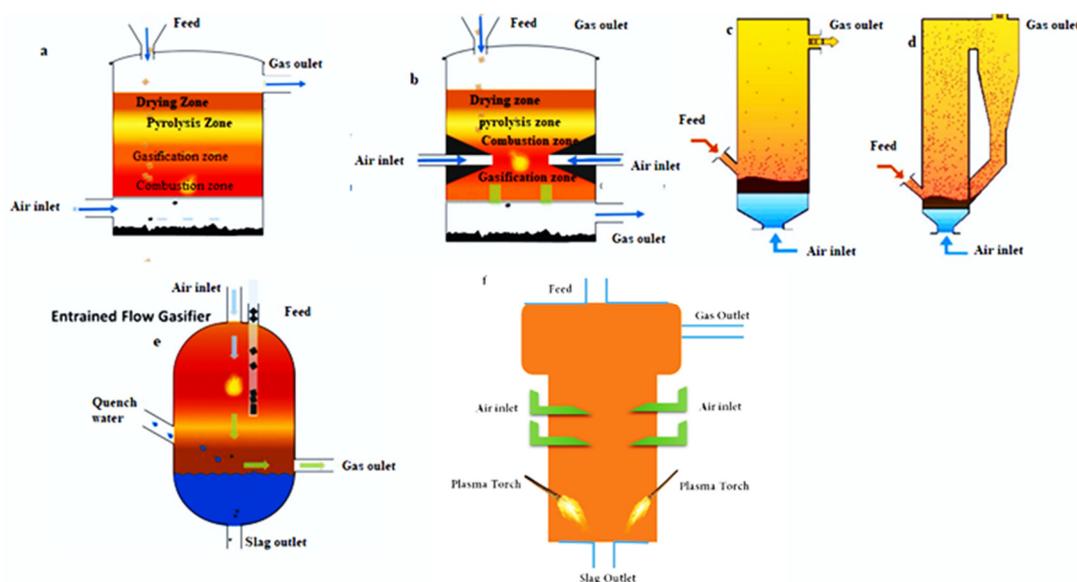


Figure 3. Schematic Diagram of (a) Updraft gasifier (b) Downdraft gasifier (c) Bubbling bed gasifier (d) Circulating bed gasifier (e) Entrained flow gasifier, (f) Plasma Gasifier [46,48,49]. Images were drawn with permission from sources [48]. Copyright 2021, Elsevier.

2.2. Influencing Parameters on Production Yield of Gasification Products

The thermochemical decomposition of biomass in the climate of air/oxygen depends on different parameters for example, reactor configuration, feedstock type, operating conditions like equivalence ratio, temperature and pressure, which finally affect the product gas quality. The impact of all of the aforementioned factors on production yield is explained below.

2.2.1. Effect of Biomass Characteristics

Biomass is a heterogeneous combination of organic and inorganic materials comprising multiple solid and liquid phases with varying concentrations. Because of the wide variety of biomass fuels (agricultural wastes, energy crops, forestry wastes, industrial wastes, and so on), it is critical to properly characterize them, as this will affect the design plan of the plant converting them to electricity. In different biomass types, cellulose (about 50% on a dry basis), hemicelluloses (10–30% in woods and 20–40% in herbaceous biomass), lignin (20–40% in woods and 10–40% in herbaceous biomass), and extractives are accessible in varying degrees, and these degrees influence item dispersion [68]. The cellulose and lignin contents of biomass are two significant parameters to evaluate the pyrolysis and gasification characteristics. Lv et al. investigated the influence of cellulose and lignin on biomass gasification using six different kinds of biomass with cellulose contents ranging from 55% to 85% and lignin contents ranging from 10% to 35% [69]. The higher the cellulose content, the faster the pyrolysis rate of biomass, which slows as the lignin percentage increases. Furthermore, the gasification process was heavily influenced by char structure and the interaction of cellulose and lignin. Increasing the cellulose content increased the gasification's peak temperature and lengthened the gasification period. High content syngas is made with high (cellulose + hemicellulose)/lignin ratios. Lignin produced more tar than cellulose and hemicellulose. Blasi and Branca et al. [70] observed that holocellulose (cellulose and hemicellulose) transforms mostly into liquids (tars), whereas lignin degradation produces char and gas. A direct relationship exists between the chemical composition of biomass and gas produced from gasification. In a study of gasification, Hanaoka et al. [71] revealed that cellulose created high measures of CO₂ and CH₄ in the product gas whereas Yang et al. [72] reported that lignin contributed to high H₂ yields in the gasification process. Herbaceous plants have loosely bound fibres with a smaller amount of lignin, whereas woody plant species have sluggish growth and are formed of tightly bonded fibres with a hard outer surface. The two most important definitive variables in determining the suitability of plant species for further processing as energy crops are the proportional quantities of cellulose and lignin. The biomass should be prepared in accordance with the gasifier in which it will be treated. The pre-treatment of biomass has a significant influence on gasification results. Pre-treatment is a required step in the thermochemical conversion of biomass that involves structural modification to overcome the recalcitrant character of biomass. Improving biomass characteristics is essential to increase the energy use efficiency of biomass. Physical, chemical, and biological pre-treatment procedures are used, with physical treatment being the most common for thermochemical conversion routes. Physical treatment methods for biomass intended as feedstock for thermochemical conversion processes include milling, chipping, briquetting, pelleting, and torrefaction. The drawback of utilizing pre-treatment technologies are high costs to obtain a pre-treated product with minimum degradation of vital components [73].

2.2.2. Effect of Moisture Content

The moisture content of the feedstock is also an important factor that affects syngas composition and gasification efficiency. In biomass, moisture may exist in two states: free and equilibrium. As the moisture content of the feedstock rises, it makes a bothersome effect on the conversion as additional energy is required for water evaporation. With moisture content below 15%, bed temperatures stay more or less constant [74]. Feed stocks such as municipal sewage sludge, and black liquor have a high moisture content of about 60% to 80% whereas wood has less moisture content [75]. A thorough understanding of the relationship between calorific value and moisture content in biomass and municipal waste was presented by Themelis et al. [76]. They suggested that feedstocks with higher moisture content have a lower relative heating value, necessitating the drying of these materials prior to the gasification stage. McKendry recommended that the biomass' moisture content should be under 10–15% for a better gasification reaction [77]. To overcome the difficulty of ash fusion in a downdraft gasifier there is a necessity for the feedstock to have a water

content of less than 25% [78]. Chopra et al. [79] and Beohar et al. [80] reported that equilibrium moisture content relies upon relative humidity and air temperature. As the moisture content of the biomass increases, so does the rate of biomass consumption, lowering reaction zone temperatures owing to the energy required to evaporate the fuel and, as a result, affecting gasifier performance and end-product quality. Martinez et al. [42] focused on the impact of molecule size and moisture content of the biomass feedstocks and the air/fuel proportion on the gasification cycle as far as gas quality goes. The influence of moisture content on the gasification process in a downdraft gasifier using air as the gasifying medium has been studied by various approaches. High moisture content reduces the net calorific value of the producing gas, lowering its heating value and lowering gasification productivity. Likewise, the tar part of the producer gas increments with an increment in the moisture in the biomass. With high moisture content, more air is needed to combust the biomass and therefore the amount of CO₂ goes up and CO decreases. CO₂ content at low moisture varies between 5% to 10% due to lower availability of carbon levels and at the higher moisture content of 40%, the content may increase to 15% and higher [81].

2.2.3. Effect of Equivalence Ratio

Equivalence ratio (ER) is the most powerful factor in fixed/moving and fluidized bed reactors [82] that significantly impacts on the composition of producer gas. It is calculated by the ratio of the actual air-fuel ratio to the stoichiometric air-fuel ratio. ER fixes the measure of air provided for gasification. In air gasification, increasing the equivalence ratio increases the rate of gas production. As the ER increased, the gasification temperature increased due to the increase in exothermic processes. Low equivalence ratios, on the other hand, lead to lower bed temperature, which favours lower gas production and higher tar formation. The ER value for effective gasification is found to be between 0.19 to 0.43. A value of 0.3 is considered to be a theoretical optimum and all the gasifier designs were based on the same [83]. The volumetric rate of air can be calculated from the ER value for a given biomass consumption rate. In agreement with many studies conducted by Garcia et al. [84] and Tinaut et al. [85], the amount of air supplied to downdraft moving bed gasifiers controls the biomass consumption rate. The increase in ER increases the nitrogen content sharply in producer gas due to the availability of more nitrogen in the gasifying medium. On the other hand, when steam was utilized as a gasification medium, then the syngas would not have nitrogen. Xue et al. [86] and Gai et al. [87] used torrefied miscanthus and corn straw with a comparably higher concentration of nitrogen in feedstock and showed a good percentage of nitrogen content in the gas. Therefore, the value of ER must be optimized as the high N₂ content is undesirable and can decrease the heating value of the gas. The ER has a comparative impact on the H₂ and CO content. The majority of researchers find that the CO and H₂ content decreases with ER. Skoulou et al. [88] studied the effect of ER on the H₂ and CO content. The effect of ER on CO₂ changes with different studies in the literature. However, it can be concluded that the ER and the amount of air don't have any impact on the water gas shift reaction. The content of CH₄ decreases as the ER increases and the majority of studies affirm this. Therefore, high ER values are not recommended for gasification. Generally, CH₄ content may vary from 1% to 3% for air gasification.

2.2.4. Effect of Temperature

Temperature is also the key factor that affects the gasification rate and overall performance of the gasifier as shown in Table 2. Since all homogeneous and heterogeneous reactions are reversible in general, the equilibrium of any reaction may be shifted by varying the temperature. Among different operating conditions, the most extreme temperature of the reaction zone is crucial in deciding carbon conversion all through the oxidation and gasification reactions, gas yield, calorific value, cold gas efficiency, gas composition, tars and char content in the gasification cycle]. The temperature variation among different gasifiers can lead to different compositions of syngas. From the literature, it can be found that there

is a dominant impact of temperature in gasifiers on the composition of the gas [89]. The higher the temperature, the better the cracking and lower the tar content. Higher temperatures, i.e., 700 to 900 °C, increase the reaction rates of the oxidation and reduction zones, resulting in improved gasification, which creates H₂, CO, and eliminates hydrocarbon. To produce syngas of high calorific value and low tar content the oxidation temperature should be between 800–950 °C and the reduction zone should lie between 650–900 °C in a downdraft gasifier [89]. As the bed temperature rises, it favours endothermic gasification reactions (water gas reactions, secondary cracking, and reforming of heavy hydrocarbons). These endothermic reactions favour the production of H₂. The content of hydrogen in the fuel also has a significant influence, which was observed by Ramanan et al. [81] using charred cashew nut shells as fuel. Hence, hydrogen content in the syngas was about 10–15% using this fuel. Most of the studies show that CO₂ content reduces as the temperature increases since Boudouard reactions ($C_{(s)} + CO_2 \rightleftharpoons 2CO$) dominate at a temperature above 850–900 °C, consuming CO₂, and increasing CO content. High temperature also favours destruction and reforming of tar leading to a decrease in tar content and an increase in gas yield [90]. The oxidation reactions and water gas shift reactions take place at low temperatures below 250 °C which produce CO₂. The decrease in the maximum reaction zone temperature affects the gas composition. Either gasification medium, steam or air affects practically all reactions occurring in the gasifier. Steam generally favours the amount of CO₂ instead of air as the gasifying specialist. The higher the hydrogen content in the fuel, the higher the measure of CO₂ can be obtained. CO concentration increases with ascent in temperature because of heterogeneous and endothermic reactions like water, gas and boudouard responses. The temperature in the gasifier bed does not influence the CH₄ concentration in the syngas. Thus, the amount of CH₄ remains practically consistent at high as at low temperatures in all studies. Kumar et al. [91] also declare that the equivalence ratio does not have a strong impact on methane. The amount of CH₄ is higher in a fluidized bed gasifier as compared to a downdraft gasifier, which varies between 2–4% using air as gasification medium. Most of the studies show the abatement of N₂ in the syngas with the expansion in temperature. N₂ can be in the syngas if air is utilized as a gasification medium. The amount of nitrogen content varies between 30–60% in the syngas. At the higher temperatures, low amounts of particulate matter and tar content were observed, which reduces the cost of cleaning producer gas. Fuel moisture absorbs its latent heat of vaporization and subsequently, high moisture content in the fuel can lessen reaction temperature, resulting in incomplete gasification, thus degrading the gas quality.

2.2.5. Effect of Particle Size

The particle size of the feed essentially influences the final results. The fuel particle size impacts the time fundamental for the gasification cycle to occur just as a satisfactory reactor size. The rate of thermal diffusion inside the particles diminishes with an increase in particle size, subsequently bringing about a lower heating rate. The fuel to be gasified requires an average particle size to keep a specific biomass consumption rate just to keep a suitable pressure drop inside the reactor without the improvement of particular channels. A smaller particle size empowers a higher producer gas quality and a decrease in the reactor size. For a fixed bed gasifier, particle size ranges from 20–80 mm, while for a fluidized bed gasifier it is still lower, in the order of ~1 mm or smaller. Edrich et al. [92] have shown that the gasification rate is highly influenced by the particle size. The gasification rate increased from 0.1 to 1.0 min⁻¹ when the particle was decreased from 19.05 mm to 5.00 mm during the gasification of wood in a fixed bed gasifier. The speed at which fuel particles heat up decreases as particle size increases, resulting in the production of more char and less tar. Kumabe et al. [93] used particle size in the range of 0.5 to 1.0 mm for both coal and biomass in the gasification of woody biomass and Li et al. [94] took the particle size of 0.42 mm for biomass in a fluidized bed gasifier. The suggested maximum particle size for a downdraft gasifier should be less than 5 cm [42]. Perez et al. [95] conducted a downdraft reactor experiment and discovered that biomass (pine bark) reacts differently depending on

its size. They discovered that as the particle size is increased, biomass consumption rates, fuel/air equivalent ratios, maximum process temperatures, and, as a result, flame front velocity decreased. They discovered that the ideal biomass particle size is 2–6 mm. Reed and Das [96] in their study on downdraft fixed bed gasifiers expressed that the feedstock size decides the trouble of fuel feeding and its conduct in the reactor. Large particles contain greater heat transfer resistance and hence the actual temperature inside the particle is lower, which leads to the occurrence of the devolatilization process [97].

Table 2. Impact of various factors on the gasification process.

Feed Stock	Reactor Type	Experimental Conditions					Results Outcome	References
		Temperature	Equivalence Ratio	Moisture Content (% wt)	Gasification Medium	Particle Size		
Palm Kernel Shell and high volatile bituminous coal	Top lift updraft	600–800 °C	0.26–0.34	6 and 2	Air	4.9–2.3 mm 4.7–9.5 mm	H ₂ /CO ratio—0.57–0.59, 0.49–0.51 and 0.42–0.46 at 70, 85 and 100 vol% biomass blends	[98]
Soybean	Batch tank	500 °C	-	5.33	Air	80–100 mesh	CO—15%, CO ₂ —30%, CH ₄ —37% and H ₂ —18% at	[99]
Wood chips	Fixed Bed downdraft	847 °C	0.335	13.2	Air	-	80%. Co-gasification results in the formation of bio-methane.	[100]
Rice husk	Quartz Fluidized bed	700 °C		8.67	Air	0.15 mm	H ₂ —11.89%, CO—12.38%, CH ₄ —4.58% C ₂ H ₄ —1.19% and C ₂ H ₆ —0.98%	[101]
Garden waste and LDPE	Autothermal Downdraft	700–900 °C	0.3	13.57	Air		Heating value of the gas increased from 3.5 MJ/Nm ³ to 4.7 MJ/Nm ³ . Cold gas efficiency increased from 43.8% to 61.8%.	[102]
Rice Husk, Rice Husk + Sawdust, Rice Husk + Bamboo dust	Circulating Fluidized-bed	750–900 °C	0.19–0.35	8.7–9.33	Air		Blending of biomasses significantly improves the producer gas in terms of H ₂ production and energy output as well as gas yield.	[103]
Eucalyptus wood	Open top-downdraft	800–1000 °C	0.3–0.4	9.2	Air		Producer gas obtained with high calorific value of 3.709 MJ/Nm ³ . CO and H ₂ of 13% and 10% at ER i0.309.	[104]
Biomass waste	Moving Grate	200–800 °C	0.28		Air	5 × 20 mm	Cold gas efficiency—64.79%, CO ₂ —9.94%, H ₂ —15.03% and CO—22.72%	[105]

2.2.6. Effect of Gasification Medium

Air, CO₂, steam, oxygen, nitrogen or mixtures are the gasifying mediums used in biomass gasification [106]. Execution of processes with air, unadulterated steam, and steam oxygen blends on the gasification of biomass were examined and it was determined that unadulterated steam had a superior performance as far as functional conditions (taking into consideration lower response temperatures) and producer gas structure (giving unrivalled H₂ yields and LHV esteems) [107]. Overall diverse gasifying mediums produce

gas with varied calorific worth. Air is regularly utilized as a gasification medium as it offers simplicity in operations and doesn't rely upon complex modern foundations and utilities. The only limitation with the technology is the production of gas with low heating value, i.e., 4–7 MJ/Nm³ due to the syngas dilution by the nitrogen present in the air and H₂ contents for electricity production and heat generation [67]. If steam or a combination of steam and oxygen is used for gasification, it produces average heating value gas, i.e., 10–18 MJ/Nm³ and higher hydrogen content [108]. Oxygen enriched air is very expensive which makes it less competitive and provides synthesis gas with a medium heating value of 9–15 MJ/Nm³ [109].

3. Upgradation of Biomass-Derived Synthesis Gas

Syngas is the significant result of the gasification of renewable and non-renewable sources like coal and lignocellulosic biomass. CO, hydrogen, CH₄, and a low quantity of light hydrocarbons, nitrogen, oxygen, and carbon dioxide, are also present [110]. This combination of gases might be used for an assortment of uses, including power generation and chemical manufacturing [111]. According to the literature, synthesis gas has the following undesirable characteristics for fuel applications:

- Particulate matter, slag resulting in emission problems
- High condensable tar leading to fouling
- Trace metals, H₂S and NH₃ causing environmental problems
- High ash content

The above mentioned undesirable characteristics make the synthesis gas useful in heating applications, but their direct use in internal combustion engines is not yet possible [112]. Particulate matter and tar removal could be achieved either by treatment during gasification or by cleaning the syngas after gasification. During gasification, modifications of the gasifier, better-operating parameters and use of additives or catalysts reduce the particulate matter and tar [43,113]. To take out particulate dust and tar from syngas following gasification, a variety of mechanical techniques have been employed, including cyclones, bag filters, baffle filters, ceramic filters, fabric filters, rotating particle separators, wet electrostatic precipitators, and water scrubbers [114]. Hasler and Nussbaumer et al. [114] found that utilizing mechanical techniques, accomplishing a 90% particle removal was more straightforward than accomplishing a 90% tar evacuation. Through the steam reforming process, tar may be further transformed into gas. Catalysts are required to speed up the process, which might be a low-temperature reforming reaction (350–600 °C) or a high-temperature reforming reaction (500–800 °C). Naturally occurring catalysts like dolomite [115], and stable metals like nickel or alkalis such as KOH [116] are used to efficiently reform tar. Spray and wash towers are suitable for removing nitrogen-containing contaminants in synthesis gas. The methods have a practical advantage as absorbent can be regenerated as an ammonium salt [117]. Sulphur impurities in syngas are typically found as hydrogen sulphide (H₂S) or carbonyl sulphide (COS), and they can be eliminated independently or in combination with other acid gases like CO₂. After being burned in a cogeneration system, the H₂S and NH₃ can create SO₂ and NO_x emissions. Furthermore, H₂S and NH₃ can cause corrosion issues in equipment. The sulphur-containing compounds in synthesis gas can be removed using wet or dry cleaning processes [118]. For acid gas removal, several methods employ physical or chemical adsorption or a mix of both. Removing acid gases with physical and chemical adsorption will be the most probable solution for mass CO₂ removal from syngas in commercial applications. Solvent, sorbent, and membranes are the most common CO₂ collection and separation methods. As CO₂ sorbents, several materials such as activated carbon, zeolites, lime, alkali oxides, silver oxides, silica gel, alumina, and metal-organic framework have been utilized [119]. In addition to the above-mentioned pollutants, the syngas consists of a variety of additional contaminants like mineral and metallic trace elements. The concentration of these trace pollutants, on the other hand, is quite low. Trace pollutants like Hg, As, Se, and Zn should be kept to a minimum in the Fischer-Tropsch

process, preferably in the ppb range. Lime, activated carbon, zeolite, and silica, to name a few [120].

4. Utilization of Biomass-Derived Synthesis Gas

4.1. Evaluation of Gasification Products as a Potential Fuel Source

Gasification of biomass yields the valuable product synthesis gas ($\text{CO} + \text{H}_2$), and a by-product of biochar [121]. These products have ideal properties for use as fuel in different heat and power production systems or can be modified to diesel and gasoline grade hydrocarbons as presented in Figure 4 [122].

4.2. Use of Synthesis Gas

The utilization of synthetic gas is recorded as follows:

1. As a fuel in biomass integrated gasification heat and power cycle (BIGCC) for electrical power generation and heating [123].
2. Used as fuel in boilers, heaters, and heat exchangers for the generation of steam or heating applications [124].
3. For the production of methanol used as a fuel or used as a precursor for chemicals like acetic acid, methyl acetate, formaldehyde, ethylene, propylene, and dimethyl ether [125].
4. For the production of bio-based hydrogen which can be used in fuel cells and to manufacture fertilizers and for hydrotreating.
5. Using Fischer-Tropsch synthesis, transportation fuels like gasoline, kerosene, jet fuel, diesel and heavy products like wax can be produced [126].
6. For ethanol production by synthesis gas fermentation using microorganisms [127].

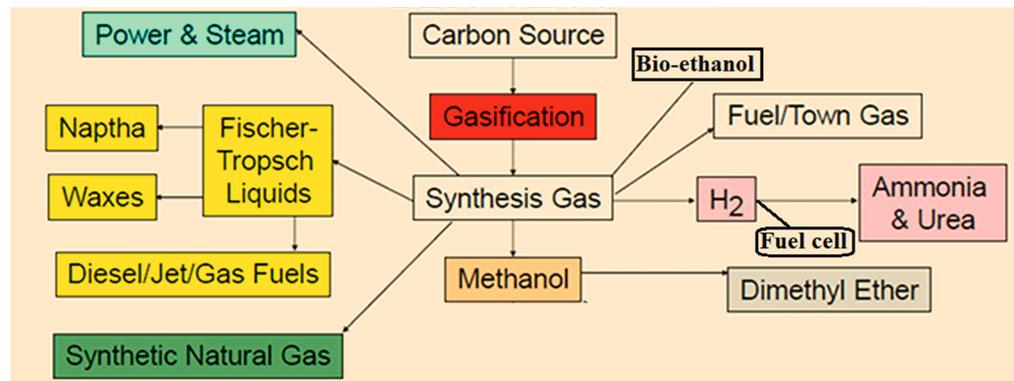


Figure 4. Applications of synthesis gas [128].

Combustion Behaviour of Synthesis Gas

Many authors have studied the flame properties of pure methane and air-blown gasification syngas fuels made from bituminous coal, wood residue, maize core, and wheat straw [129].

Whenever circulated power is under 100 kW, internal combustion engines (ICEs) powered by syngas generated from the gasification of biomass, specific fuel consumption values for biomass and solid waste range from 0.5 to 5.8 kg/kWh. Nonetheless, a huge restriction of ICEs working on Syngas is power derating [130]. Spark ignition engines (SIEs) are frequently employed in syngas applications because of their ease of adjustment, particularly in the air/fuel intake system [131]. Outflows of CO_2 and SO_2 reciprocals from biomass power were likewise found to be 67 and 18 times lower, individually, than those from fuel oil [132].

4.3. Use of Biochar

Gasification of solid biomass contains char, a carbonaceous substance with a distinctive graphitic microstructure, or ashes, which are the unstable inorganic species in biomass. Lignin and, less significantly, hemicellulose are the essential sources of char delivered by biomass gasification. The solid's carbon part is nebulous and untidy, with elemental carbon (50–80% weight), trace inorganics, and heavy molecules, for example, polyaromatic hydrocarbons (PAHs) [133]. Char's aromatic hydrocarbons and functional groups have continuous development in the formation process; therefore, it lacks a definite chemical structure [134]. Generally, char is taken for secondary gasification for further gasification. Char can be used as a predecessor of activated char (AC), manures or impetuses for the breakdown of NO_x (nitrogen oxides) forerunners, the age of producer gas utilizing CO₂ and tar changing, etc. [135]. When employed for tar reformation, char can outperform commercial and costly catalysts [136]. Biochar may also be utilized as a soil conditioner and as a catalyst for biodiesel synthesis via hydrolysis, dehydration, and transesterification. Another biochar application is as an adsorbent and addition to building materials [137].

5. Conclusions

The gasification process is best suited to produce synthesis gas by thermochemical methods. Downdraft gasifiers are preferred over entrained flow gasifiers and fluidized bed gasifiers. Gasification reaction temperature, biomass characteristics, moisture content, equivalence ratio, particle size and gasification medium are the variables that have the most impact on the gasification process. Controlling these factors promises better-quality syngas with a suitable level of tars and particulate matter. Synthesis gas of high calorific value and low tar content is obtained at higher temperatures (800–950 °C). Advanced methods like the UNIQUE gasifier concept, combining the gasifier reactor, conditioning in a single reactor, multistage and plasma gasification give advantages to expand the yield, streamline the cost and work on the effectiveness. In addition, technical challenges like tar formation, ash, and particulate matter should be addressed through the proper design of the downdraft gasifier.

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