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Steam Gasification of Biomass for Hydrogen Production – A Review and Outlook

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ABSTRACT

This article summarizes various biomass gasification methods and explains their advantages and disadvantages. First, theoretical aspects of gasification and the variety in reactor designs are overviewed. Despite the eminent effect of reactor design on gas product quality, gasification agents remain the dominant factor that determines the gas composition. Steam gasification is a thermochemical process that promotes organic carbonaceous substances into carbon monoxide and hydrogen while reducing the presence of dilutants. However, several obstacles during gasification and downstream processing have to be overcome to achieve adequate maturity. Gasification characteristics of steam were compared to the other gasification agents, including air, oxygen and CO_2. The key performance parameters affecting steam gasification include raw material properties, additive and catalytic materials. While the key operating parameters include operating temperature, residence time, superficial velocity, equivalence ratio and steam-to-biomass ratio. Finally, the techno-economic evaluation and challenges facing the commercialization of steam gasification were discussed.

1. Introduction

Climate change problems resulted in many initiatives and research to reduce CO_2 emissions of greenhouse gas. Short-term solution involves the direct reduction of greenhouse gas through the gas capture techniques which is still very limited in capacity [1]. While medium and long-term solutions involve exploiting the different types of renewable energies. Solar energy influences directly or indirectly most of the other renewable energies. Common use of solar energy is by direct use for electricity using photovoltaic (PV) panels, direct thermal utilization or water-cooled PVT combined heat and power to utilize waste heat waste of PV [2-4]. Second major renewable energy resource is the wind energy where wide range of research is aimed at the improvement of current vertical-axis and horizontal-axis wind turbine technologies [5,6]. Biomass is the third major energy contributing to energy resources, excluding traditional hydro power. Biomass is a variable controlled energy mix that may be used to supply enormous quantities with low solar and wind energy in the renewable

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energy combination of wind, solar, and biomass energy. Biomass has been a prime energy source for thousands of years, and still makes up more than 10% of the energy supply worldwide, ranking as the fourth most significant source of energy in the global since civilization has recognized how to generate fire [7]. Furthermore, biomass was the main energy source for cooking and other thermal applications in rural regions in the 20th century which was in some places the only accessible energy source. By early 2000s, biomass consumption as fuel in rural areas was accounting for about 60% of fuel consumption in India, while 50% of the population still relied on traditional cooking using biomass fuel in Indonesia before the government initiative in 2007 to promote the use of LPG for cooking [8-10]. In South-East Asia, oil palm is one of the largest potential sources of biomass energy especially in Malaysia and Indonesia that has expanded oil plantations [11].

The global production of palm oil reached 410.7 million ton in 2019 which occupied about 28.3 million hectares of plantation land area [12]. Indonesia, Malaysia, and Thailand contributed about 88% of the global production as shown in Figure 1. However, the increase in production capacity of oil palm in the past decade only increased by 15.6% in Malaysia unlike the other countries where it doubled in Thailand and increased by nearly 3 folds in Indonesia [12]. Oil palm industry contributes to the majority (about 85%) of biomass waste in Malaysia, 10% for Municipal Solid Waste (MSW) and 5% for other biomass resources [13,14]. However, the environmental impact of oil palm trees plantation on soil and water has to be evaluated before any new expansions [15]. The solid biomass waste from palm oil mill can be directly used in steam boiler for power generation to run the mill as well as the excessive steam that can be used for other processes of palm oil production [16]. Boiler chimney thermal losses can be utilized for power production as well [17]. Hence, waste-to-energy concept can be considered as a major contributor towards low-carbon policy [18]. The merits of biomass use as a fossil fuel are; (1) A significant contribution to carbon footprint reduction due to biomass neutrality, (2) new jobs opportunities in rural places, (3) reducing the country dependency on fossil fuels and hence contributing to the economic growth of countries, and (4) the wider range availability, making the access to biomass easier in comparison to fossil fuels [19-21].

Solid biomass in its solid form is considered as low-grade fuel with low energy density and poor combustion characteristics. Therefore, it can be upgraded into higher quality solid fuels, or converted into liquid biofuels and gaseous fuels. Torrefaction is an attractive way of large-scale method of upgrading biomass, however, the different factors such as feed stock condition, temperature, and duration have to be optimized to achieve economic mass production [22]. Further biomass quality upgrade is through carbonization to produce biochar as a high-quality fuel or pure carbon that can be used as supercapacitor electrode [23,24]. Biomass can also be converted into liquid bio-oil through pyrolysis process. Biomass content plays major role on the pyrolysis output, where high lignin content in biomass will result in higher biochar yield while higher cellulose and hemicellulose content increases bio-oil yield [25]. As the pyrolysis is an endothermic reaction, external heat supply is needed such as electrical heaters and microwave ovens [26]. The use of Acid-based pre-treatment of lignocellulosic biomass was found to be essential to increase the productivity yield and quality of the biofuel products [27]. Another investigated biomass pre-treatment is the use of liquid hot water which has less side effect on environment with good enhancement of the biofuel production yield [28]. The pre-treated hemicellulose can be chemically synthesised into wide range of liquid biofuels such as biodiesel, 2-Methylfuran and 2,5-Dimethylfuran that can replace petroleum fuels [29-31]. Another important upgrade of biomass is by converting it into high-grade gaseous fuels such as hydrogen through pyrolysis and gasification processes [32].

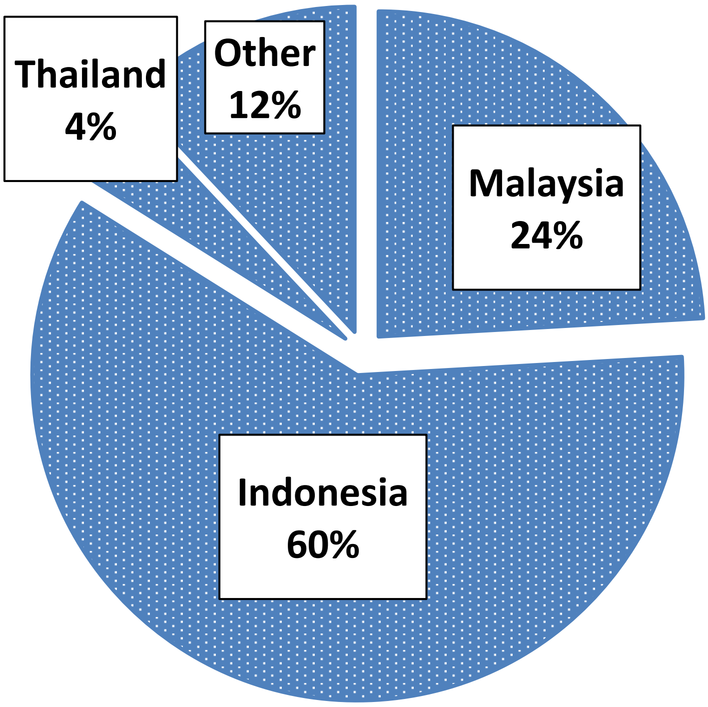

Fig. 1. Global production of palm oil in 2019 [12]

Gasification technology is crucial for the utilization of biomass, as it gives more flexibility for the use of different feedstock types of materials. This allows the conversion of all biomass types into syngas through gasification which includes hydrogen (H_2), carbon dioxide (CO_2), carbon monoxide (CO) and some methane (CH_4) with some higher hydrocarbons (typically <1%), including ethane and ethylene as well as tar compounds such as benzene, toluene, and naphthalene, etc. [33]. Thus, syngas can be used to generate various energy and energy careers power, heat, hydrogen, biofuels, biomethane, and other chemicals. The energy and exergy potentials have shown considerable variation for the different gas compositions of syngas from air gasification, with CO and CO_2 having the highest and lowest potentials, respectively [34]. Additional uses of syngas from air gasification include the technical processes of Fischer- Tropsch (FT) synthesis for the production of oils, dimethyl ether (DME), methanol, ethanol, or hydrogen [35-37].

Biomass gasification is accomplished through carbon partial oxidation at elevated temperatures with a controlled flow of reaction agents such as steam, and air, as well as oxygen. Commonly, the use of steam and oxygen enhances the gasification performance compared to air since the dilution of nitrogen (around 50 vol.%, in syngas) is avoided in the gasification process. Therefore, the use of steam and oxygen are preferred for gasification since the heating value of syngas can be elevated in the range of 10-20 MJ/Nm^3 [38]. Air is considered as an alternative to oxygen because it is extremely expensive to utilized oxygen for gasification. Due to nitrogen dilution, air gasification drops the quality of gas down to 4-6 MJ/Nm^3 [39].

On the other hand, the use of steam for gasification can be good alternative, since it enhances the gas quality up to 20MJ/Nm^3 [40]. Unlike air or oxygen gasification, steam gasification has less CO_2 contamination, however, external heat input is required as the process is endothermic. Practical alternative is through a self-sustained energy supply by burning some of the biomass in secondary combustor to generate the heat needed for the steam reactions. One way to achieve this is through the dual-fluidized-bed configuration. In this design, the heat is supplied by the secondary fluidized bed combustor and the hot bed material is circulated to the primary fluidized gasifier chamber [41].

Kaushal and Tyagi [42] reviewed some of the existing pilot plants using dual fluidized bed technology for biomass steam gasification and the main challenges facing the up-scale of such technology. Double-fluidized bed technology was also proposed for hydrogen production from steam gasification [41]. Another method to provide the heat is through the combustion of some of biomass in air-steam gasification approach. However, the gas will still be contaminated with N_2 but to a lesser extent. For air-steam gasification of biomass with coal-bottom ash catalyst, several factors were investigated including S/B ratio, equivalence ratio, reaction temperature, and catalyst loading and their effect on gas quality [43]. Sharma and Sheth [44] showed that steam can be added directly to the existing conventional downdraft gasifiers without system modification reaching S/B ratio up to 1.2 to enhance hydrogen production and elevate the quality of syngas. Production of hydrogen from biomass through wide range of technologies was widely investigated. Main technologies for hydrogen production included biomass thermochemical conversion, bio-oil reforming from biomass pyrolysis, supercritical water gasification, biological fermentative process of biomass and photosynthesis biological water shift reaction [45,46].

1.1 Scope and Limitation

There is huge potential for developing renewable alternative biofuels from various types of biomass waste to replace fossil fuels in the transportation, aviation and power generation sectors. Steam gasification maintains the way within the valuable economic balance for green hydrogen production in large commercial scales. The scope of this review covers the theoretical background of thermochemical reactions of biomass, the design and geometry of the biomass conversion reactors, the potential reaction agents with more infuses on steam as the main agent in this study and finally, the main factors affecting the production of hydrogen from steam-biomass reaction. Moreover, in-depth discussions at the end of the review will focus on the outlook of current and prospective biomass utilization and the potential technologies that can be involved. The aim of this review is to

i. Analyze the prospects of biomass gasification and the in fluence of oxygen, air and steam used as the gasification agents on the process.
ii. Discuss key parameters considered in steam gasification and the influence of hydrogen yield for the different types of biomasses.
iii. Discuss the role of different catalysts on hydrogen production yield during steam gasification.
iv. Discuss the technical challenge and economic potential of different types of gasification.
v. Discuss the biomass energy systems and their integration with other renewable resources.

Data resources for this review are extracted mainly from: academic research papers (71.8%), academic review papers (24.7%), academic books/chapters (2.9%) mostly published under the Web-of -science and Scopus database, and government reports (0.6%). The study is limited to the academic view of the theories, while the industrial perspective and technology evaluation is limited due to the lack of published reports on the new technologies.

2. Gasification Technology

Gasification is thermochemical reaction commonly dominated by partial oxidation that mainly produces gas products (water, CO, CO_2, H_2, and gaseous hydrocarbons), a small amount of solid char, ash and traces of condensable tars and oil compounds. Moreover, gasification can convert the low or negative–value feedstock into products [47]. The gas product is commonly referred to as producer gas when it is heavily contaminated with dilutants such as N_2 and CO_2, while pure $CO+H_2$ gas is known as syngas [39]. Steam, air, oxygen and CO_2 were tested widely as gasification agents for the reaction. This makes the use of producer gas more flexible and easier compared to the original biomass (for example, it can be used in gas turbine and gas engines or as a chemical feedstock for production of liquid fuels). Biomass gasification go through very complex chemical reactions with multiple steps that solid biomass should go through during the thermochemical conversion which are as following [48].

2.1 Drying

Biomass moisture is reduced in this mechanism. Usually, biomass moisture content fluctuates between the level of 5% to 35%. Drying occurs at an approximate temperature between 100 to 200°C with <5 % reduction of the moisture present in biomass.

2.2 Pyrolysis

In the absence of air and oxygen, this is a thermal decomposition of the biomass. As a result, the volatile matter is reduced in biomass, hydrocarbon gases are released from the biomass, which is ultimately reduced to solid charcoal. At the temperature under 350°C the hydrocarbon can be condensed to produce bio-oil and liquid tar.

2.3 Oxidation

It is an exothermic reaction between atmospheric oxygen, and solid carbonized biomass which causes CO_2 formation. Biomass also contains hydrogen, which is oxidized to produce water. This exothermic reaction only occurs in air and oxygen gasification with the availability of oxidizer, and it provides the heat needed for the other reactions. Moreover, excess oxygen is further used for the reduction reaction.

2.4 Reduction or Gasification

Solid char and other products from pyrolysis are converted into producer gas during this process. For air and oxygen gasification, the reaction occurs at sub-stoichiometric presence of oxygen at 800-1000°C. The global gasification reaction shown in Eq. (1) can predect producer gas volume composition by knowing the elemental analysis (mass%) of biomass (C%, H%, O% and N%) [49].

$$\frac{C\%}{12}C+\frac{H\%}{1}H+\frac{O\%}{16}O+\frac{N\%}{14}N+\boldsymbol{a}(O_2+3.76N_2)\rightarrow \boldsymbol{b}CO_2+\boldsymbol{d}CO+\boldsymbol{e}CH_4+\boldsymbol{f}H_2+\boldsymbol{g}O_2+\boldsymbol{h}N_2+\boldsymbol{i}H_2O \tag{1}$$

Therefore, the vol.% of dry producer gas is determined as $CO\% = (d/b+d+e+f+g+h)\times 100$, as an example for carbon monoxide. The reactions shown in Eq. (2) to Eq. (4), occur when using steam as gasifying agent as following [50]

water-gas shift reaction

$$\mathrm{C}\ +\ \mathrm{H}_2\mathrm{O}\leftrightarrow\ \mathrm{CO}\ +\ H_2, \Delta H\ =131\ \mathrm{kJ/mol} \tag{2}$$

water-gas shift reaction

$$\mathrm{CO} + \mathrm{H}_2\mathrm{O} \leftrightarrow CO_2 + H_2, \Delta H = -41 \text{ kJ/mol} \quad (3)$$

steam methane reforming

$$\mathrm{C}H_4 + \mathrm{H}_2\mathrm{O} \leftrightarrow \mathrm{CO} + 3H_2, \Delta H = 206 \text{ kJ/mol} \quad (4)$$

and steam tar reforming as shown in Eq. (5) [39].

$$\mathrm{Tar} + \mathrm{H}_2\mathrm{O} \leftrightarrow \mathrm{CO} + H_2, +\Delta H \quad (5)$$

On the other hand, when CO_2 is used as the gasification agent, Boudouard reaction occurs as shown in Eq. (6) [51].

$$C + CO_2 \leftrightarrow 2CO, \Delta H = 172 \text{ kJ/mol} \quad (6)$$

Another important reaction is the dry reforming of methane into syngas using CO_2 as the reaction agent as shown in Eq. (7) [52].

$$CH_4 + CO_2 \leftrightarrow 2CO + 2H_2, \Delta H = 258.9 \text{ kJ/mol} \quad (7)$$

The main parameter to evaluate the performance of the gasifier is through the cold-gasefficiency (CGE) using Eq. (8), where thermal biomass input is compared to the thermal output of producer gas after cooling it to ambient temeprature [49].

$$\mathrm{CGE} = (\dot{m} \times LHV)_{ProducerGas} / (\dot{m} \times LHV)_{Biomass} \quad (8)$$

Where ($\dot{m}$) is mass flow rate (kg/s) and LHV is lower heating value (MJ/ Nm^3). Another factor to evaluate the flexibility of the gasifier in terms of its output power range is the turndown ratio. It is calculated as the ratio of the maximum energy output (or producer gas flow) to the minimum output at which efficient operation can be sustained. For fixed-bed gasifiers, turndown ratio is commonly in the range of 3-4 [53].

3. Gasifier Designs

Gasifier designs can be classified as: fixed beds, fluidized beds and suspension or entrained flow. Fixed and fluidized bed types cover wide range of raw biomass sizes from small chips up to large blocks while entrained flow is only applicable for fine powder biomass particle size.

3.1 Fixed Bed Gasifier

The oldest and most used reactors for gas production are fixed-bed gasifiers. However, the use of fixed–bed gasifiers at large scales (more than 10MW) is declining in industrial sectors because of the scale-up challenges [54]. But smaller scales are frequently used for distributed heat and power applications due to their good thermal efficiency [55]. Their wide usage and popularity are mainly due to the simple structure, flexible operation and high reliability. Depending on the producer gas flow direction, fixed-bed gasifiers are divided into up-draft, downdraft, and cross draft [56]. For updraft and downdraft gasifiers using air as a gasification agent, the composition of the gas through volume has been observed to be generally within the expected limits such as CH_4 (1-3%), CO_2 (5-15%), H_2 (5-15%), and CO (20-30%) [57]. Also, it suffers from the high N_2 dilution in the range of 40-50% when using air, which limits net LHV to 4-6 MJ/Nm^3 [53]. It also increases the volume of producer gas with the requirement for high-capacity downstream gas cleaning equipment. Usually, fixed bed gasifiers produce smaller particle loads of ash and char compared to fluidized bed gasifiers [58].

The zones inside the reactor show different reactions based on their distance from the air supply inlet and the direction of producer gas flow. The regions inside the reactor are distributed as: drying, pyrolysis (devolatilization), combustion, and reduction zones. Drying removes moisture from raw material at low temperature and the absence of oxidizer. Pyrolysis removes volatiles from the raw material at higher temperature in the absence of oxidizer through thermal decomposition of the material where high fixed carbon content is then passed to the oxidation and reduction (gasification) zones to be converted into gas and ash. In comparison with other designs, the disadvantage of fixed-bed gasifiers includes the lower gas quality with higher tar content, while an advantage of these gasifier is the simplicity of the design.

3.1.1 Updraft gasifier

In this design, the gasifying agent (air, steam etc.) is supplied into the gasifier from the bottom side via a grate, and biomass is supplied into the gasifier from the top side. The gasification agent passes upwards towards the biomass feeding level while it is converted into producer gas, hence the name updraft as shown in Figure 2(a). While biomass feed at the top of the gasifier drops by gravity down to the pyrolysis zone. In this zone feed material is decomposed into volatile tar and char**.** Eventually, the volatile-free biomass is converted in the reduction zone where main gases are produced. The rest of the biomass finally enters the grate, in which solid char is combusted at 1000℃ when it gets in contact with the air supply. The remaining ash falls through the grate, once char is consumed.

Heat from combustion is drifted upwards along with the remaining oxidizer and CO_2 where biomass is reduced into producer gas. Due to the gas cooling when it is drifted upwards, some of the tar is condensed on the falling biomass while large amounts leave the gasifier with the producer gas. Thus, this type of gasifiers suffers from its high tar content that typically exceeds 100 g/Nm^3 which limits its usage for thermal applications rather than power production [59]. The producer gas is cooled down to approximately 200°C while passing through the drying zone, leading to significant enhancement in cold gas efficiency in comparison to other types of fixed-bed gasifiers [60]). Further enhancement of the gasifier efficiency can be achieved by injecting steam which enriches producer gas with hydrogen [59].

3.1.2 Downdraft gasifier

Similar to the other gasifier designs, biomass feeding port is at the gasifier top while air is injected at a special constriction zone known as the throat where the diameter is reduced. Unlike the updraft configuration, producer gas is not allowed to exit the gasifier from the top, thus, it is pushed to the bottom of the gasifier, hence the name downdraft. Downdraft gasifiers consist of four separate zones from top to bottom including drying zone followed by pyrolysis zone, oxidation zone at the throat, and lastly reduction zone below the throat as shown in Figure 2(b). The producer gas leaves the upper middle zone and descends to the lower middle zone, pushing it via the throat. Air is injected at the throat, creating oxidation zone with high temperature in the range of 1000-1400℃. Reducing the cross-section area at the throat reduces the cooling effect near walls, which provides better chance for cracking the tar formed at the pyrolysis zone. This includes thermal decomposition on tertiary tars which are hard to crack and require high temperature. Therefore, downdraft is the most suited type of fixed-bed gasifiers for power generation in internal combustion (IC) engines due to its low tar (approximately 1 g/Nm^3) and particle content [61]. For downdraft gasifier design, the cross-section area of the throat must be considered carefully to avoid excessive pressure drop while maintaining acceptable balance for good tar cracking performance. Heart load value of 0.9 (m^3/cm^2.h) was reported to be the upper limit to avoid excessive pressure drop (FAO, 1986). Heart load can be calculated using Eq. (9) [53].

$$\text{Hearth Load } (\text{m}^3/\text{cm}^2.\text{h}) = \text{Gas flow rate } (\text{m}^3/\text{h})/\text{Throat surface area } (\text{cm}^2) \tag{9}$$

The early terminology of hearth load was known as superficial velocity (SV) and using (m^2) unit for the surface area will provide the normal velocity unit (m/s) for SV, hence the name. Some of the drawbacks for this type design include the poor thermal efficiency and difficulty in handling biomass with high moisture and ash content.

3.1.3 Cross draft gasifier

The fuel feeding port is similar in all fixed bed designs at the top due to the absence of mechanical means to move biomass other than the natural drop by gravity. On the other hand, air inlet port is located at one side of the gasifier and producer gas is released from the opposite side in a crossflow manner across the gasifier as shown in Figure 2(c). The air enters at the hot combustion zone where most of it is consumed to generate the needed thermal power while the rest is passed horizontally to perform reduction reactions while pyrolysis and drying are higher in the vessel [62]. The gas leaving the unit has a temperature of around 800-900°C, and the ash is removed from the bottom of this unit. Consequently, this design suffers from lower overall efficiency with high tar content. To achieve higher gas heating value, the feed's average biomass moisture content should remain in the range of 15-20 wt. %. Therefore, it is usually not required to pre-dry the biomass feedstock [62].

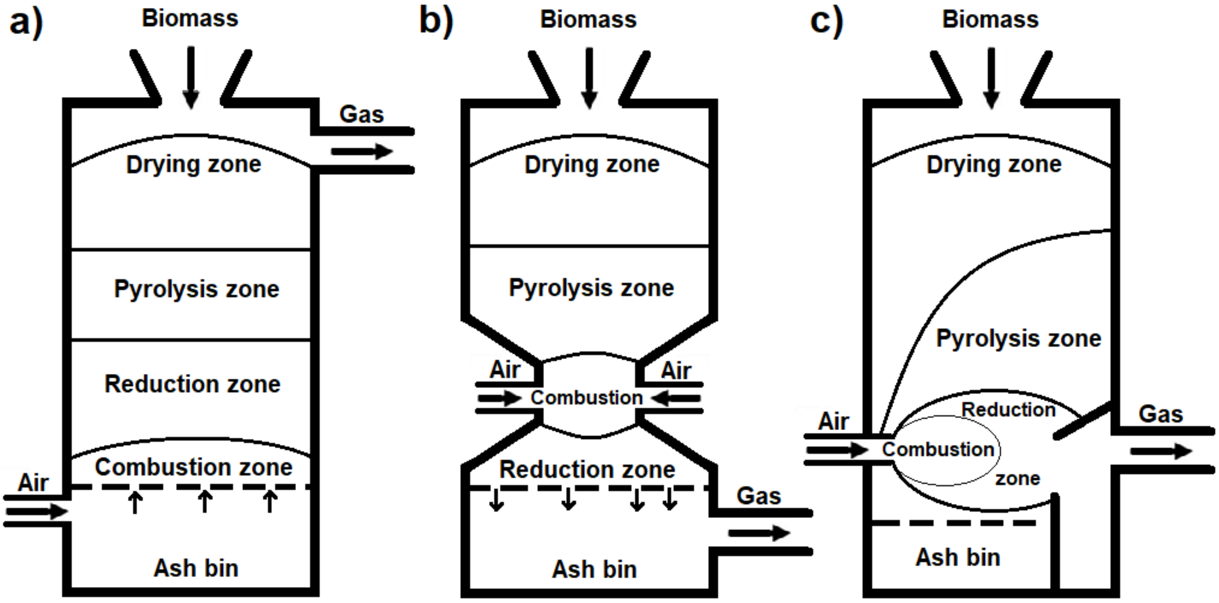

Fig. 2. (a) updraft gasifier; (b) Downdraft gasifier; (c) cross-draft gasifier [63]

3.2 Fluidized Bed Gasifier

Fluidized beds emerge as the best among the technologies used for biomass combustion due to their flexibility in fuel type and great performance. For many years, gasification in fluidized bed (FB) has been largely used in coal gasification. In comparison to fixed bed gasifiers, FB has the advantage of distributing temperature uniformly in the reduction zone. The uniform temperature is obtained using a bed of fine granular materials such as silica sand and dolomite under which air circulates to achieve bed fluidization. Intense bed fluidization promotes a solid circulation and favours mixing hot bed material, hot combustion gases, and biomass feed. Another important advantage of FB is the flexibility with respect to different fuel types and shapes [64]. In FB, the average 10g/Nm^3 tar level is a moderate rate of tar in comparison to fixed-bed gasifiers. Tar formed is a mixture of secondary as well as tertiary tars [65].

Lack of sufficient fluidization in FB gasifier caused by bed agglomeration is also referred to as defluidization, which is a severe issue. The common problem is the "coating-induced" agglomeration of the fine granular forming materials in FB as a precursor to defluidization in commercial-scale installations. The coating forms on the surface of the bed sand particle during the operation of the reactor, and the content of sodium of biomass is facilitated at specific critical coating thickness and temperature levels. As a consequence, the silicate and alumina-silicate melting points are lowered in the bed particle through sodium. Another major concern when used for gasifying herbaceous biomass is the agglomeration associated with FB gasifiers. Promising solutions have been proposed for different biomass feedstocks [66]. These solutions are primarily based on lowering and controlling the temperature of bed. Currently, two main types of fluidized bed gasifiers are used: a) circulation bed, b) bubbling bed [67]. Internal circulating fluidized bed was proposed to provide some of the advantages of the other two FB types, but still being under research and development stage [68].

3.2.1 Bubbling fluidized bed gasifier

Bubbling fluidized bed gasifier is considered as the oldest reactor design. The gasifying agent (air, steam, etc.) is supplied from the bottom side of the reactor through a grate in a bubbling bed gasifier. A moving bed of fine-grain substance is placed above the grid into which a continuous feed of biomass is introduced. By regulating the air/biomass ratio, the bed temperature is regulated around 700 to 900°C. The biomass is pyrolyzed in the hot-bed and forms tar and char gaseous compound. Heavy tars compound is broken when it interacts with the hot bed materials to produce syngas, thus, lowering tar contamination in the range of 1-3g/Nm^3 [62].

3.2.2 Circulating fluidized bed gasifier

This design shares similar theory with the older bubbling FB design but with vigorous fluidization created by the higher air inlet velocity. The vigorous bed material fluidization causes uninterrupted circulation of the bed material out of the reaction vessel top to be passed back to the bottom of the vessel. To separate the solids substances from producer gas, a cyclone separator is utilized, where char, bed substance and ash are segregated and returned to the reaction vessel. These gasifiers can accommodate high-capacity biomass throughputs, allowing it to be scaled-up for higher power outputs [67]. Circulating fluidized bed gasifier can operate at high pressure to allow pressurized producer gas to be directly fired in gas turbine without requiring further compression, which was demonstrated in a pilot plant [69].

3.3 Entrained Flow Gasifier

This gasifier design is usually utilized in coal gasification, since it allows fuel to be slurry-fed, which lowers the cost of high temperature solid-fuel feeding system. This design is distinguished by short residence time, high pressures, high temperatures and large capacities. It can also be divided into three categories based on their agent, including air, steam or oxygen. Varying the reaction agents can directly affect the quality and compositions of the gas as well as the product yields. Suspension gasifiers commonly utilize fine pulverized coal (0.1-0.4mm) which is the main factor to achieve higher energy density and power scale-up capability [58]. However, these entrained flow gasifiers are not allowed for fibrous substances (e.g., wood), which limits the types of biomass substances that may be used in this design and needs further biomass pre-treatment to be used [65].

3.4 Gasification Agents

The most utilized and most popular approach to transform hard biomass into producer gas is through thermochemical conversion process [70]. Yielded gas property is not only affected by the design and structure of the reactor, but also affected by the reaction agents. The studies about gasifying agents which also belong to the gasification exhibition included mainly air, O_2 enriched air, steam, pure O_2, CO_2, steam-CO_2, air-steam, and O_2-steam [71-77]. However, minimum examination was conducted to determine gasification agents' influence on gasification execution [78]. In general, the gasifier atmosphere governs the quality of the producer gas. For example, a lower heating value is obtained if one uses air as a gasifying agent, mainly due to the gas contamination with nitrogen dilutant as it is dominating the air supply, additional to CO_2 dilutant from biomass combustion [79]. However, the syngas is produced with a medium heating value using either a combination of O_2-steam or steam [80]. Furthermore, the addition of steam to air enriches the producer gas with H_2 which elevates the heating value.

3.4.1 Air

The use of air as gasification agent is the most popular option due to its abundance and ease of use. However, the efficiency of air gasification is highly dependent on temperature and the equivalent ratio. In fact, the higher the air temperature input to the gasifier, the higher heating value of producer gas that can be achieved [81]. Furthermore, since air contains approximately 79% nitrogen, the major drawback of air gasification is that producer gas is highly diluted, thus, increasing gas separation cost [82]. This can drop the quality of the gas to the minimum combustibility limit of about 3.5 MJ/Nm^3. As a result, the use of air as gasification agent is often restricted to the on-site heat and power applications since the gas cannot be stored or transferred economically due to its low energy density [83].

3.4.2 Oxygen

Oxygen is widely investigated as one of the promising alternatives for air since it elevates the producer gas quality up to the medium heating value around 10MJ/m^3. However, the main disadvantages of using oxygen as gasification agent are the high cost of pure oxygen supply as well as the contamination of CO_2 and O_2 in the output gas. As a result, oxygen is often paired with other gasification agents to provide the heat needed from biomass oxidation for gasification reactions [84].

3.4.3 Carbon dioxide

The use of CO_2 reaction agent has been closely associated with pyrolysis investigations in many studies as both pyrolysis and CO_2 gasification reactions are fully endothermic and require external heat supply to be sustained [85]. The former represents thermal degradation reaction in the presents of neutral atmosphere commonly N_2, while the latter utilizes Boudouard reaction shown earlier in Eq. (6) in an atmosphere of CO_2 [86]. The main obstacle for CO_2-gasification is the heavy dependence on temperature where reaction temperature of 700°C is barely adequate to activate the Boudouard reaction, unlike in steam-gasification, with less than satisfactory conversion yields [87]. One method to overcome this obstacle is by implementing various types of catalytic materials to enhance the reaction at lower temperatures [88]. Another tested method is to increase the amount and size of active-cites on the micro-structure of char surface by injecting steam [76].

3.4.4 Steam

The use of steam in methane reforming reaction shown earlier in Eq. (4) is still the main technology used for the hydrogen global mass production [89]. Steam gasification is well-proven and well-establish technology. Steam gasification has several benefits, including the production of renewable hydrogen with high yield from variety of biomass feedstock and the cleaner product with minimal environmental effects. Many research studies have been conducted on steam gasification has [79]. It was shown that steam gasification could increase the yield of hydrogen production by three folds in comparison to air as the agent [80]. The first reaction between steam and carbon in biomass as well as the higher hydrocarbon compounds results in the production of pure syngas which require moderate amount of energy input to activate the reactions [50]. Moreover, if syngas and methane are exposed for extended periods to steam at adequate temperatures, additional reactions occur which consumes CO and CH_4 and convert them into H_2 and CO_2 [50]. According to the reports in literatures, pure steam gasification produced more gaseous CO_2, light hydrocarbons, and tar compares to air gasification. In the reduction stage, a sequence of reactions occurs between drying and pyrolysis products. Finally, char decomposes into gaseous products in the reaction zone [92-94].

Table 1 compares the effect of air, oxygen and steam as gasification agents on performance of the gasification process and quality of producer gas [95]. The main advantages of using steam as the gasification agent are

i. First: to elevate the heating value of the output producer gas, by reducing the non-combustible dilutants including vapor as well as N_2.
ii. Second: to reduce sulfur as well as nitrogen elements from the output fuel that can represent large portion of the raw input material, thus, reducing the potential of pollution.
iii. Third: to reduce the output ratio of (C/H) carbon to hydrogen through the enrichment with hydrogen.

Table 1
Comparison between Air, steam, oxygen gasification processes [95]

	Air	Oxygen	Steam
Gas heating value, MJ/Nm^3	Low 4-6 CO H_2 water, CO_2, HC Tar, N_2	High 10-15 CO, H_2, HC, CO_2,	High 15-20
Average producer gas composition	H_2 – 15%, CO – 20%, CH_4 – 2%, CO_2 - 15%, N_2 - 48%,	H_2- 40%, CO – 40%, CO_2- 20%,	H_2 – 40%, CO -25%, CH_4 – 8%, CO_2-25%, N_2:2%,
Reactor temperature, °C	900 -1100	1000 -1400	700 -1200
Cost	Low	High	Medium

Reaction steps inside the steam gasification reactor can be illustrated through the following simple reactions. The initial step shown in Eq. (10) for the heat effect on biomass through thermal decomposition and devolatilization

$$\text{Pyrolysis of biomass } + \text{Heat} \rightarrow H_2 + CO + CO_2 + HC_{\text{gases}} + \text{Tar} + \text{Char} \tag{10}$$

The second step in the reaction chain inside the reactor represents the interaction between steam and biomass shown in Eq. (11) and Eq. (12)

$$\text{Biomass} + \text{Steam} + \text{Heat} \rightarrow H_2 + CO + CO_2 + CH_4 + \text{Light and heavy HC} + \text{Tar} + \text{Char} \tag{11}$$

$$\text{Biomass} + \text{Air} \rightarrow H_2 + CO_2 + CO + N_2 + CH_4 + \text{Light and heavy HC} + \text{Tar} + H_2O + \text{Char} + \text{Heat} \tag{12}$$

Therefore, air-steam gasification transforms raw biomass feedstock into gases (CO, CO_2, CH_4, H_2, and light HC), char and tar with low amount of N_2, while being fully or partially self-sustained depending on the amount of air used. Table 2 shows the main reactions associated with the steam gasification [96].

Table 2
The chain of reactions during steam gasification [96]

Reaction	Types	ΔH (kj/mol)
Primary devolatilization		
Biomass → CO, CO_2, CH_4, C_2H_4 carbon,		
Primary Tar ($CHxOy$)		
Tar cracking and reforming		
Primary tar → CO, CO_2		
CH_4, C_2H_4, H_2,		
Secondary Tar		
Homogenous gas-phase reaction		
Tar→ C, CO, H_2	Combustion (oxidation)	-242
$H_2 + 0.5O_2 \rightarrow H_2O$	Combustion (oxidation)	-283
$CO + 0.5O_2 \rightarrow CO_2$	Combustion (oxidation)	-110
$CH_4 + 0.5O_2 \rightarrow CO + 2H_2$	dry reforming reaction	+247
$CH_4 + CO_2 \rightarrow 2CO + 2H_2$	steam reforming reaction	+206
$CH_4 + H_2O \rightarrow CO + 3H_2$	water gas-shift reaction	-40.9
$CO + H_2O \rightarrow CO_2 + H_2$		
Heterogeneous reactions		
$C + O_2 \rightarrow CO_2$	Oxidation of carbon	-393.5
$C + 0.5O_2 \rightarrow CO$	Partial oxidation	-123.1
$C + CO_2 \rightarrow 2CO$	Boudouard reaction	+159.9
$C + H_2O \rightarrow CO + H_2$	Water-gas reaction (steam reforming)	+118.5
$C + 2H_2 \rightarrow CH_4$	Methane and production	-87.5

4. Main Factors of Steam Gasification

The main key variables to be considered for the characterization of steam gasification can be divided into two main categories. First category includes the material characteristics including raw biomass and additives such as sorbent and catalytic materials. The other category includes the functional factors such as operating temperature, superficial velocity, reaction residence time, equivalence ratio (ER) and S/B ratio.

4.1 Biomass Type and Shape

Biomass is mainly composed of cellulose, hemicellulose, and lignin, with some variation in composition from type to type. These compounds govern the way biomass will degrade [97]. More lignin and cellulose dominance in biomass feedstock will generally produce more gaseous product, which in turn augments the production of H_2. However, hydrogen production is also dependent on biomass fundamental nature including the amount of moisture and alkali contents [98]. Variety of biomass species have so far been investigated to produce hydrogen through steam gasification from biomass. Some of them include: pine sawdust, coffee husk, waste water sludge, palm oil waste, municipal solid waste, lignocellulosic char, sawdust tea waste, spruce wood, hazel nut, yellow pine, moses, algae, woodchips, wood saw dust, waste wood, coir pith, almond shell, black liquor, wheat straw and cedar wood [99-108]. The effect of biomass material type and size on hydrogen production yield and conversion efficiency have been reviewed [97].

Table 3 demonstrates H_2 output yields and energy performance during hydrogen production from steam gasification from different biomass types. Investigation results show the effect of the biomass type, catalytic reaction and operating conditions on H_2 yield and the resulted energy effectiveness of the conversion. Biomass size and shape can also play a significant role on the reaction activation and efficiency. Grinding biomass into small particles increases the reaction contact area significantly per unit mass of the input biomass, as the particle diameter is inversely proportional to the free surface area. The different reactions inside the reactor are greatly affected by the porosity and shape of the material as the increase in surface area not only increases the gasification rate but also the other reactions such as drying and devolatilization due to the effective heat transfer [109]. The enhanced gasification reactivity ultimately increases the production of hydrogen and Carbon monoxide while reducing CO_2 content through the dry reforming of methane shown earlier in Eq. (8). Superb performance was also demonstrated when using pine sawdust at 600°C in catalytic steam gasification where 72.83 mol/kg H_2 yield was achieved [110].

Table 3
Hydrogen generation and conversion effectiveness from steam gasification of various biomass types

Biomass	Exergy effectiveness	H_2 yield (mol/ kg)	Operating conditions	Reference
Pig compost	48.71	35.93	950°C, Fuel particle size <0.2	Wang *et al.,* [109]
	44	32.45	950°C, Fuel particle size 0.2-0.5	Wang *et al.,* [109]
	38.69	28.54	950°C, Fuel particle size 0.5-1.0	Wang *et al.,* [109]
	34.6	28.54	950°C, Fuel particle size 1.0-2.0	Wang *et al.,* [109]
Coconut shell	39.81	38.65	950°C, S/B = 1.69	Moghadam *et al.,* [111]
	43.37	42.1	950°C, S/B = 3.1	Moghadam *et al.,* [111]
Palm kernel shell	17.11	13.9	675 °C, S/B = 1.5	Khan *et al.,* [112]
	60.52	49.15	675 °C, S/B = 2.5	Khan *et al.,* [112]
Pine sawdust	32.03	28.55	900°C S/B = 0.2	Pala *et al.,* [73]
Wood chip	33.37	28.30	900°C S/B = 0.2	Pala *et al.,* [73]
Wood residue	32.92	27.86	900°C S/B =0.2	Pala *et al.,* [73]
Coffee bean husk	42.17	34.32	900°C S/B = 0.2	Pala *et al.,* [73]
Green wastes	37.90	30.32	900°C S/B = 0.2	Pala *et al.,* [73]
Municipal solid waste	49.38	32.94	900°C S/B = 0.2	Pala *et al.,* [73]
Sawdust	11.69	9.02	650°C CaO/C = 1	Wei *et al.,* [113]
Rich shell	10.28	6.56	650 °C CaO/C = 1	Wei *et al.,* [113]
Cotton stalk	11.31	8.26	650°C CaO/C =1	Wei *et al.,* [113]
Corn stalk	12.81	8.79	650°C CaO/C = 1	Wei *et al.,* [113]
Wheat straw	12.98	8.53	650°C CaO/C = 1	Wei *et al.,* [113]
Food waste	26.12	32.30	650°C CaO/C = 1	Wei *et al.,* [113]

The production of char and tar decreases with the increasing reactivity. It was reported in literatures that the particle size of raw biomass showed significant effect on hydrogen production [114]. Large particles increase resistance to heat transfer, leading to incomplete pyrolysis and more residual char [115]. Another study also confirmed that reducing particle size enhanced the efficiency of carbon conversion and hydrogen yield [116]. It was stated that the use of fine particles promotes water-gas, carbon gasification reactions and secondary cracking reactions which increased CO and hydrogen content in producer gas [117]. It was also shown that the reduction in particle size significantly improved gasification efficiency and reduced tar contamination in producer gas [118].

4.2 Moisture Content

As the high precipitation is crucial for biomass growth, many type of raw biomass fuels retain high moisture after being extracted as agricultural waste. Moreover, most of biomass types suffers from the hygroscopic behaviour as the raw materials tend to absorb moisture from atmosphere due to the porous nature. This causes several biomass storages issues due to mold growth as well as the increase in the required power needed for grinding [119]. High moisture content in raw biomass consumes large amount of heat necessary for steam gasification reactions to allow water to be converted into steam. Moreover, it will reduce the effectiveness of heat transfer to raw biomass and reduce the initial devolatilization stage required to start the various steam reactions with char. Therefore, additional pre-drying of raw biomass with high moisture content is required to achieve stable steam gasification process. It was shown that stable steam gasification technology is achieved when moisture content in biomass was less than 35% [98].

4.3 Sorbent Materials

Carbon-neutral emission footprint can be achieved when using biomass. However, if CO_2 is captured and not released during the production process, carbon-negative emission footprint can be achieved [120]. Many studies investigated the effect of sorbent materials to capture CO_2 from hydrogen production [121]. The following sorbents were used in the gasification process: rhodium, aluminium oxide, dolomite, nickel-based sorbent, metal-based sorbent. The fundamental principal is to modify the balance composition of the producer gas by extracting CO_2 from the gasification process, which increase hydrogen-rich gas production. It was also reported in literatures that solid-based sorbents are more efficient than liquid-based sorbents, and CaO was recommended as viable and economic sorbent [121-124].

4.4 Catalytic Materials

The use of catalytic materials can provide lower-energy alternative route to the activation of the reaction at a lower temperature. The implementation of catalytic materials for biomass steam gasifiers was shown to improve the reaction rate and activate the reactions at lower temperatures [125]. Higher hydrogen concentrations in producer gas and hydrogen production yield from biomass steam gasification were increased when using catalysts [126]. The interest in studying the effect of catalysts on the hydrogen production from biomass has increased in recent years with the examination of wide range of catalysts. Dolomite, alkaline metal, alumina non-based catalytic material such as silicate Na_2CO_3, K_2CO_3 $ZnCl_2$ and rare materials such as Ru- based and Pt-including are among the studied catalysts. The preliminary function of the catalyst is to promote heat and mass transfer among particles commonly through the increase of reaction and contact surface area. This in turn increases the effectiveness of the different reactions inside the gasifier such as the different wet and dry reforming reactions as well as the thermal decomposition and cracking. H_2 and CO yields can be increased by increasing the reactivity of the water gas, co-shift as well as steam-methane reforming reactions. Catalysts are not only initiating gasification reaction, but they also contribute to the destruction of tar. Tar cracking can be caused by the simple thermal decomposition or through the tar-steam reforming shown earlier in Eq. (5) which can promote hydrogen production. Thus, in general, hydrogen yields are increased by increasing the efficiency of gasification reaction as well as the destruction of tar [127].

Dolomite, Ni-based catalyst and alkaline metal oxide catalyst were successfully utilized to promote steam gasification reaction [126]. A study showed that the use of alumina-silicate material, alumina, and Ni-based catalyst heavily controlled producer gas composition, but showed less influence on gas yield [128]. They observed that alumina-silicate catalysts are more effective for char raw material while Ni-based catalysts are more appropriate for lighter hydrocarbons. It was shown that catalytic materials have positive effect not only on tar cracking but also on producer gas quality and yield [129].

The use of calcined dolomite and nano-NiLaFe/g-Al_2O_3 catalysts for hydrogen generation through steam-gasification reaction of palm oil waste was examined as well [130]. The result indicated that unlike the calcined dolomite, nano-NiLaFe/g-Al_2O_3 showed substantially greater influence on hydrogen production. Hydrogen production from municipal solid waste steam gasification was examined using various catalysts such as NiO/MD (NiO on modified dolomite) and NiO/g-Al_2O_3 [131]. The results showed that hydrogen production was more affected by NiO/MD than NiO/g-Al_2O_3. The production of hydrogen through steam gasification of compost sample was also studied using $Ni_2Al_2O_3$ and olivine catalysts [132]. The results indicated that olivine significantly affected hydrogen production compared to Ni_2Al_2 O_3. Hydrogen production was also investigated for sugarcane bagasse steam gasification using $NieAl_2O$, Ni_2MgO, and Ni-dolomite catalysts [133]. With the help of $Ni_2Al_2O_3$, the highest hydrogen yield was achieved, followed by Ni2MgO and Ni-dolomite.

The generation of hydrogen through steam-gasification of sewage sludge using various catalytic materials including K_2CO_3, KOH, Na_2CO_3, and NaOH was examined [134]. The results indicated that the impact occurred in the following order: NaOH > Na_2CO_3 > K_2CO_3, > KOH. Using same fuel, other catalysts including CaO, CaO-3A, CaO-3A-Fe, and CaO-3A-Ni were also tested [135]. The effect of the catalysts was arranged as follows: CaO-3A-Ni >CaOeNi> CaO-3A-Fe > CaO-3A >CaO. Generally, the influence of the catalytic material on hydrogen production could be positive, negative, or negligible as can be seen in Table 4. However, these effects also vary by other parameters such as S/B, biomass characteristics, gasification temperature, etc.

Table 4
Effect of various types of reaction catalysts on the production of hydrogen through steam gasification of wide range of biomass fuels

Biomass	Catalysts	H_2 production (mol/kg)	Reference
Olive waste	-	25.60	González *et al.,* [136]
	$Zncl_2$	31.99	
	dolomite	28.33	
Palm oil waste	-	19.88	Li *et al.,* [130]
	Calcined dolomite	26.49	
	Nano-Ni/γ-Al_2O_3	50.89	
Municipal solid waste	-	10.95	Wang *et al.,* [131]
	Ni/γ-Al_2O_3	31.31	
	NiO/MD	40.34	
Sugarcane bagasse	-	25.24	Waheed *et al.,* [133]
	Ni-dolomite	28.09	
	Ni-Al_2O_3	46.69	
	Ni-MgO	44.69	
Sewage sludge	KOH	10.31	Gai *et al.,* [134]
	K_2CO_3	11.24	
	NaOH	12.83	
	Na_2CO_3	12	
Rice hush	-	31.04	Li *et al.,* [137]
	Nano-NiO/γ-Al_2O_3	51.04	
Palm kernel shell	Cao	45.20	Khan *et al.,* [138]

Appropriate catalysts should be utilized according to the conditions of biomass gasification to improve the conversion of carbon for hydrogen production. Generally, alkali metals like KOH, NaOH, K_2CO_3, Na_2CO_3 $KHCO_3$, and Ca $(OH)_2$ can support biomass steam gasification, but with several downsides including the difficult recovery, large loading amount, and blockages [139]. While for Ru or Rh noble metals, despite having high steam gasification activity, they are not feasible for large scale due to economic considerations [140]. Ni-based catalyst is frequently used as an effective catalyst, and it is preferable for the use in combination with other metals [141]. Additional to catalytic activity, metal oxides can also be utilized to help as external metal catalysts. Thus, Ni-based catalysts can increase the stability using a supporter of metal oxide [142]. Dolomite and olivine are natural mineral catalysts; thus, they are more feasible for large scale biomass steam gasification, but their catalyst activity is lower compared to other catalysts.

4.5 Reaction Temperature

Hydrogen production was shown to be mainly influenced by the reaction temperature in steam gasification. For the activation of water-gas shift endothermic reaction between char and steam, high temperature in the range of 600-800 °C is needed if no catalysts are used. With the temperature increase, the composition of combustible gases especially hydrogen is increased leading to the elevation of heating value. Simultaneously, the steam tar reforming reaction is easily activated which reduces tar contamination in producer gas. Moreover, CH_4 and higher hydrocarbons are converted into syngas through the steam reforming reactions. Therefore, heat supply is essential factor for hydrogen generation during the biomass steam gasification process as all reactions inside the reactor are endothermic in nature.

The effect of gasification temperature ranging from 200°C all the way up to 1100°C on hydrogen production was investigated [110]. It was shown that the effect of reaction temperature was significant where hydrogen yield was increased from 1.19 – 72.83 mol/kg when increasing temperature in the range of 200-600°C while further elevation in temperature did not show a considerable effect. Therefore, it was concluded that 600°C was the optimum temperature for the highest efficiency. Similar results on the positive effect of temperature (600-800°C) on hydrogen production have been reported on pipe sawdust, Japanese oak, white fir, rice husk, eucalyptus, sewage sludge, municipal solid waste, livestock manure compost, wood pellet, corn stalk, wood sawdust and palm kernel shell [99,121,143-149].

4.6 Reaction Residence Time and Superficial Velocity

The reaction residence time not only involves the time required to complete the reaction which is commonly manipulated by varying the flow velocity of the gasification agent, but it also involves the available space which is referred to as “space residence time” [118]. A balance has to be established during the design of the reactor considering the flow velocity of the gasification agent, mass flow of the fuel and the operating temperature to achieve adequate residence time without reducing the production capacity [150]. This provides more control to activate the slower reaction without the need to increase the reactor volume which can negatively affect the efficiency through the heat losses. Examples of the extension of the reaction residence time without the need for larger volume are the pours medium reactors and fluidized bed reactors [67,151]. The use of dual fluidized bed technology not only provides a good solution for heat supply to the steam gasification, but also provides tremendous time extension for the raw material to react. The extended reaction residence time is mainly provided through the continuous circulation of the fuel particles until they complete the reaction, but with some limitations of the feeding rate and available volume of the reactor [152]. Extending the reaction residence time was shown to be crucial especially for slow pyrolysis decomposition and devolatilization reactions [153].

Superficial velocity (SV) in m/s unit is also referred to, in some literatures, as hearth load [154]. It represents a close resemblance to the effect of residence time in terms of the balance of reaction completion and tar cracking to the efficient production rate of producer gas [155]. Higher SV up to about 4 m/s will result in fast pyrolysis and reduction of char production from this zone, while lower gas flow (and velocity) will expand the pyrolysis zone and increase tar contamination in producer gas [156].

4.7 Equivalence Ratio

As discussed earlier, steam gasification reactions are endothermic in nature and require external heat supply. However, one of the solutions is to provide limited amount of air supply that will create additional zone (oxidation) inside the reactor with exothermal reaction that provides heat to the surrounding zones. The downside is the addition of N_2 dilutant to producer gas as it is part of the air supply. The equivalence ratio (ER) is commonly calculated based on air/fuel ratio for gasification application where ER<1 represents gasification in fuel-rich condition [53]. The other type of calculation is based on fuel/air ratio which is commonly used for lean combustion applications which is not considered in this discussion. The acceptable ER (air/fuel) rage for air gasification is 0.19–0.41 [53]. Where below the range the gasification become pyrolysis dominant while above the range it become combustion dominant. Maintaining ER in the range of 0.25–0.28 for air-steam gasification of wood sawdust pellets was shown to be essential to maintain stable self-sustaining operation without any additional external heat supply [49]. This ideal ER range was also confirmed by other researchers while increasing ER will result in considerable elevation in CO_2 contamination in producer gas [74]. Moreover, the effect of ER elevation from 0.3 up to 0.38 negatively affected the heating value of producer gas showing significant drop, mainly due to the higher generation of CO_2 [157].

4.8 Steam-to-Biomass (S/B) Ratio

S/B ratio is a major performance indicating parameter that indicates the steam capacity as well as the effectiveness or the reactivity of biomass that will be translated into biomass fuel consumption. Therefore, increasing flow input is limited by the material reactivity and energy input where excessive steam flow will result in declination in gas output quality and reaction temperature. Very low S/B limit of 0.3 was observed when water was supplied into reactor jacket instead of steam and the heat from air gasification was utilized in generating the steam [49]. This can offer promising economic value as no steam boiler is needed for the system but at the expense of lower Producer gas heating value of 4.7MJ/m^3. Injecting steam to the reactor in air-steam gasification elevated the S/B up to 1.2 for furniture waste wood and S/B =1 for algae biomass, while elevating the gas heating value above 10 MJ/m^3 [44,158]. On the other hand, pure steam gasification without any air addition can elevate S/B ratio above 2 as shown in Table 5 for different types of biomass raw materials. For pure steam gasification, no biomass is consumed by combustion, thus, S/B becomes an accurate representation of biomass reactivity unlike air-steam gasification where part of the fuel mass is oxidized by air. Therefore, S/B ratio can be a useful tool since it describes the mass balance for energy calculations and can directly indicate steam reforming reactivity which is directly related to hydrogen production yield in syngas. Steam flow reduction was shown to be directly related to the reduction of carbon conversion with higher methane production. While, increasing steam flow will provide additional amounts of steam to start the steam methane reforming reaction additional to the increased carbon conversion resulting in high H_2 and CO concentrations [93]. However, the presence of excessive steam has negative effect on reaction temperature reduction which limits tar cracking. As a result, S/B has to be optimized to maintain the energy and hydrogen production balances [46].

Table 5
Comparative studied for various biomass ratio through steam gasification with respect to hydrogen production

Biomasses	Ratio = s/b	H_2 production (mol/kg)	References
Pellets wood	0.24-0.34	27.5	Campoy *et al.,* [159]
Solid Municipal waste	0.77	38.60	He *et al.,* [103]
Pine sawdust	2.70	39.40	Lv *et al.,* [160]
Pinewood blocks	0.32-0.69	44.13	Lv *et al.,* [161]
Palm oil waste	1.33-2.67	66.63-58.07	Li *et al.,* [102]
Rice husk	1.5-2.5	15.07-14.41	[137]
Pine sawdust	1.43-2.8	55.91-29.11	Luo *et al.,* [116]
Shell Palm kernel	1.5-2.5	14.35-48.97	Khan *et al.,* [138]
Shell Coconut	1.69-3.10	38.65-42.10	Moghadam *et al.,* [111]
Fir white	0.83-1.58	10.28-8.68	Acharya *et al.,* [121]
Sewage sludge	1.5-2.0	15.07-14.41	Gai *et al.,* [134]
Municipal solid waste	1.23-3.08	40.34-32.05	Nipattummakul *et al.,* [90]
Residue wood	0.5-1.0	19.06-25.40	Fremaux *et al.,* [162]

5. Techno-Economic Potential and Future Perspective of Gasification Technology

Choosing suitable steam gasifier design requires careful study of various components, including biomass raw material physicochemical properties, type and shape, the target characteristics of producer gas output, the configuration of heating system and the heat transfer mechanism to the reactor. Other than the technical aspects, economic considerations are of an utmost importance. Economic aspects include the initial cost, operating cost which is heavily influenced by the heating supply method, maintenance requirement and reliability, and finally the auxiliary systems requirement such as fuel handling/pre-treatment, and gas treatment. Fixed-bed gasifiers has shown high reliability due to the absence of any moving part and their economic value was proven through several decades of use for small and medium scales. However, the implementation of steam gasification was shown to be feasible only for air-steam gasification configuration. On the other hand, the upscale for pure steam gasification was only proven using dual fluidized bed technology with internal bed material circulation as shown in Figure 3 [41]. A pilot plant of 100 kW_{th} dual fluidized bed has demonstrated the feasibility for the use of sustainable steam gasification without external heat supply [163]. Internal bed material circulation has the advantage of better heat transfer characteristics, but still under research and development phase [30]. Fluidized bed reactors, using the steam as gasifying agent and catalytic bed materials for tar reforming, are currently the potential technology for syngas and hydrogen production from biomass waste [164].

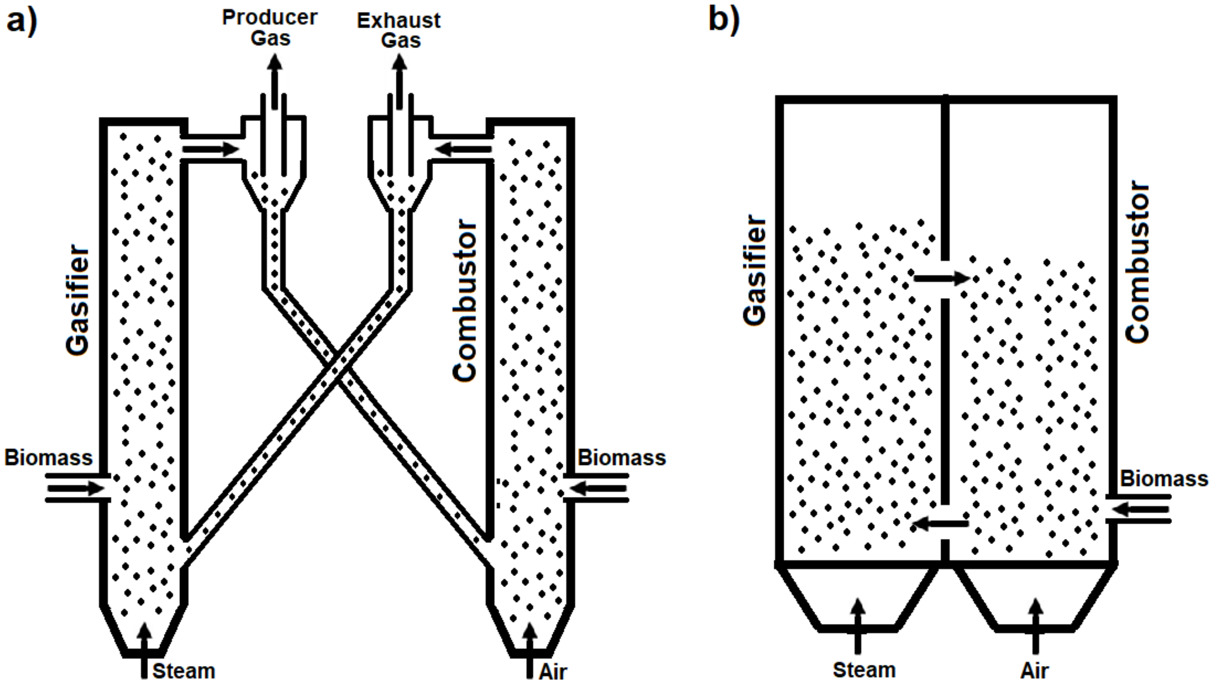

Fig. 3. Dual fluidized bed: (a) external circulating (b) internal circulating [41]

Biomass fuel can be used on-demand unlike the solar and wind energies are intermittent. Adding biomass to other renewable resources in hybrid power system reduces the need for large capacity and costly energy storage. Wide range of studies have investigated the integration of different renewable energy resources in hybrid power systems [165-167]. For these small-scale distributed generation hybrid systems, Biomass gasifiers along with IC engine generators are used to provide part of the electrical output. However, for large scale systems, gas turbines and solid oxide fuel cells driven by hydrogen-enriched producer gas can be used [168,169]. In these systems, hydrogen is produced using Proton Exchange Membrane Electrolyser which consumes part of the electrical power from the system. Large-scale hydrogen production was also proposed using steam gasification using solar heating either by a vortex flow suspended biomass rector heated directly by sun radiation or using indirect solar heating through heat exchangers [170]. To improve the heat transfer efficiency through the heat exchanger in such systems, nano-particles additives were proposed [171]. Other proposed methods to produce green hydrogen from biomass included dark fermentation of biomass with the aid of nano-additives, and the use of biogas from anaerobic digestion of biomass with steam-methane reforming [172,173]. In the future smart cities, different renewable energy resources should be integrated in the power systems to ensure the power availability on-demand without sacrificing the operating efficiency, low-carbon economy and low pollutant emissions [174].

6. Conclusions

This review provided an overview of the gasification theory and the different geometry designs and flow configurations for the gasification reactors. It also examined the suitability of steam as gasification agent to produce hydrogen enriched syngas with high heating value (HHV) compared to air, oxygen and CO_2. While air is easily accessible, nitrogen dilutes the producer gas resulting in significant drop in HHV. On the other hand, oxygen gasification is an expensive method that produces medium heating value gas with high CO_2 dilution. There have been few promising significant parameters addressed in steam gasification during the formation of enriched H_2 syngas. This included materials properties such as biomass shape, size, physicochemical properties and moisture content as well as the use of sorbent and catalytic materials. It also included the operating key factors like reaction temperature, superficial velocity, residence time, ER, and S/B ratio. As many researchers consider hydrogen to be the fuel of the future, large-scale renewable hydrogen production from biomass has not been achieved yet. Currently, the dual fluidized bed technology is the most promising technology for biomass steam gasification. On the other hand, air-steam gasification presents another economic alternative especially for fixed bed gasifiers since the supply of external heat is still a technical challenge.

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