Review Article

Cogasification of Coal and Biomass: A Review

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Recently, there has been significant research interest in cogasification of coal and various types of biomass blends to improve biomass gasification by reducing the tar content in the product gas. In addition, ash present in biomass catalyzes the gasification of coal. However, due to the fibrous nature of biomass and the large difference in gasification temperature of coal and biomass, cogasification in existing systems presents technical challenges. This paper documents research studies conducted on the cogasification of various types of coal and biomass using different types of gasifiers under various sets of operating conditions. In addition, the influence of cogasification on upstream and downstream processing is presented.

1. Introduction

Coal gasification is an established technology [1, 2]. Biomass gasification has been the focus of research in recent years to estimate efficiency and performance of the gasification process using various types of biomass such as sugarcane residue [3], rice hulls [4], pine sawdust [5], almond shells [6], almond [7], wheat straw [8], and food waste [9]. However, only a handful of peer-reviewed journal articles are available on woody biomass gasification [10–13]. Recently, there has been significant research interest in cogasification of various biomass and coal mixtures such as Japanese cedar wood and coal [14] coal and saw dust [15], coal and pine chips [16], coal and silver birch wood [17], coal, pine, and polyethylene [18], and coal and birch wood [19]. Cogasification of coal and biomass has some synergy [20]. The process not only produces a low carbon footprint on the environment, but also improves the H_2/CO ratio in the produced gas which is required for liquid fuel synthesis [14]. In addition, inorganic matter present in biomass catalyzes the gasification of coal. However, cogasification processes require custom fittings and optimized processes for the coal and region-specific wood residues.

While cogasification is advantageous from a chemical point of view, some practical problems have been associated with coal and biomass gasification on upstream, gasification, and downstream processes. On the upstream side, the particle size of the coal and biomass is required to be uniform for optimum gasification. Kumabe et al. [14] used particle size in the range of 0.5 to 1.0 mm for both coal as well as for biomass and Kezhong et al. [21] used particle size of 0.42 mm for biomass and 0.25 to 0.75 mm for coal. In addition, moisture content and pretreatment (torrefaction) are very important during up-stream processing.

While upstream processing is influential from a material handling point of view, the choice of gasifier operation parameters (temperature, gasifying agent, and catalysts) decide product gas composition and quality. Biomass decomposition occurs at a lower temperature than coal and therefore different reactors compatible to the feedstock mixture are required. Kumabe et al. [14] used a downdraft gasifier for gasification of Japanese cedar and Mulia coal, and Kezhong et al. [21] used a fluidized bed reactor for gasification of bituminous coal with pine dust and rice straw. Temperature variation among reactors can cause different compositions of syngas.

Feedstock and gasifier type along with operating parameters not only decide product gas composition but also dictate the amount of impurities to be handled downstream. Downstream processes need to be modified if coal is used with biomass in gasification. Heavy metal and impurities such as sulfur and mercury present in coal can make syngas difficult

to use and unhealthy for the environment. Also, at high temperature, alkali present in biomass can cause corrosion problems in downstream pipes. An alternative option to downstream gas cleaning would be to process coal to remove mercury and sulfur before feeding it to the gasifier.

The objective of this paper is to present a comprehensive review on up-stream, gasification and downstream processes, along with different types of gasifiers, feedstock materials, and conditions for cogasification.

2. Gasification Process

The general gasification process consists of a series of unit operations. The main unit operations are feedstock preprocessing (upstream processing), gasification, product gas cleanup, and gas utilization (downstream processing) [22]. Figure 1 shows the stepwise processes coal and biomass cogasification.

3. Upstreaming Process

3.1. Size Reduction. Coal and biomass require drying and size reduction before they can be fed into a gasifier. Size reduction is needed to obtain appropriate particle sizes; however, drying is required to achieve a moisture content suitable for gasification operations. In addition, densification of the biomass may be done to make pellets and improve density and material flow in the feeder areas.

In a biomass gasification study, Lv et al. [5] and Rapangnà and Latif [7] reported that gasification of small biomass particles (0.23 mm particles for pine saw dust and 0.28 mm for almond shells) resulted in low tar and high gas yields and high energy content. These improvements in yield and efficiency make sense, as smaller particles have larger surface area and porosity, for a given mass, which facilitates faster heat transfer rates and removal of gasification products from the solid surfaces. Kumabe et al. [14] used a particle size range of 0.5 to 1.0 mm for Mulia coal and Japanese cedar during cogasification. It was found that Mulia coal pulverized to a sieve size less than 106 μm had more sulfur in the product gas than that from the particles of sieve size ranging 0.5 to 1 mm. However, size reduction processes (e.g., hammermilling, knife milling, or tub grinders) consume energy. The energy consumed during size reduction depends on many factors including biomass moisture content, initial size, screen size, and processing equipment properties. Mani et al. [23] tested the specific energy consumption for the size reduction of corn stover, barley straw, and switchgrass. Average specific energy consumed at 12% initial moisture content of the feedstock with a hammer mill screen size of 3.2 mm was measured as 27.09, 11.04, and 27.63 kWh/t for barley straw, corn stover, and switchgrass, respectively. Due to its fibrous nature, switchgrass had the highest specific energy consumption. In the size reduction of switchgrass by means of a hammer mill with a screen size of 5.6 mm, 44.9 kWh/t of energy was consumed [24]. Given the importance of forest residues for gasification, a similar study is needed to determine the influence of particle size and specific energy
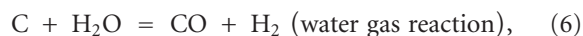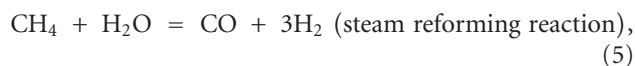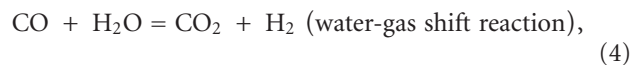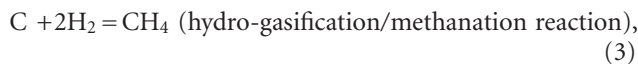
consumption for forest residues. This information will be critical to performing sustainability and economic analysis of the size reduction process.

3.2. Drying. McKendry [25] recommended that biomass moisture content should be below 10–15% prior to gasification. High moisture content reduces the temperature achieved in the gasification zone, thus resulting in incomplete gasification. Forest residues or wood has a fiber saturation point at 30 to 31% moisture content (dry basis) [26]. Compressive and shear strength of the wood increases with decreased moisture content below the fiber saturation point. In such a situation, water is removed from the cell wall which causes shrinkage of the cell wall. The long-chain molecules which make up the cell wall move closer to one another and bind more tightly. A high level of moisture, usually injected in form of steam in the gasification zone, favors formation of a water-gas shift reaction that increases hydrogen concentration in the resulting gas [15].

3.3. Torrefaction. The torrefaction process is a thermal treatment of biomass in the absence of oxygen, usually done at 250–300°C temperature to drive off moisture, decompose hemicellulose completely, and cellulose, partially [27]. Torrefied biomass has reactive and unstable cellulose molecules with broken hydrogen bonds. Torrefied biomass not only retains 79–95% of feedstock energy but also produces a more reactive feedstock with lower H/C and O/H content than the original biomass [27]. Torrefaction causes high production of H_2 and CO in the gasification process. A study showed that H_2 and CO production were increased by 7% and 20%, respectively, in gasification of torrefied Beachwood in an entrained flow reactor at 1400°C as compared to the original wood [28].

4. Cogasification Processes

While coal gasification chemistry is well established and it has been adopted for biomass gasification, the chemistry of gasification of coal-biomass mixtures has not been widely studied. Coal gasification follows a combination of the following reactions [15]:

$$2C + O_2 = 2CO \text{ (partial oxidation)}, \tag{1}$$

$$C + O_2 = CO_2 \text{ (complete oxidation)}, \tag{2}$$

$$C + 2H_2 = CH_4 \text{ (hydro-gasification/methanation reaction)}, \tag{3}$$

$$CO + H_2O = CO_2 + H_2 \text{ (water-gas shift reaction)}, \tag{4}$$

$$CH_4 + H_2O = CO + 3H_2 \text{ (steam reforming reaction)}, \tag{5}$$

$$C + H_2O = CO + H_2 \text{ (water gas reaction)}, \tag{6}$$

$$C + CO_2 = 2CO \text{ (boudouard reaction)}. \tag{7}$$

Size reduction, drying, compaction, preparation of gasifying agent — Biomass preprocessing

Preparation of coal biomass mixture ← Coal preprocessing

Size reduction, drying

Heating, chemical reactions, catalysis — Cogasification

Removal of tar and particulate matter from syngas, reforming of syngas, catalysis — Gas cleanup and reforming

Gas turbine, gas burner, fuel cell, combined heat and power (CHP) — Gas utilization

Upstream processing
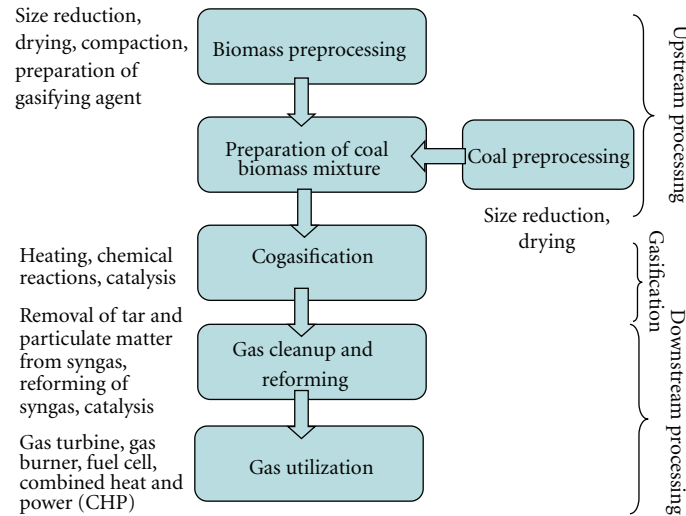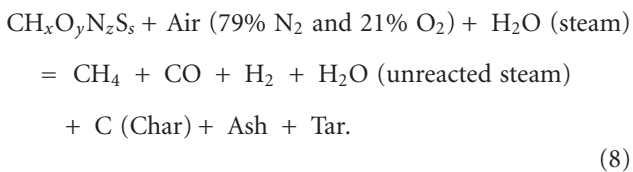
Gasification

Downstream processing

FIGURE 1: Various operations involved in the coal-biomass gasification process.

While coal is mainly carbon, biomass is a complicated mixture of complex compounds such as cellulose, hemicelluloses, lignin, extractives, and minerals. During gasification of biomass, minor oxidation (combustion) and major pyrolysis take place. The behavior of biomass pyrolysis shows drying (below 125°C), hemicelluloses, cellulose, and partial lignin decomposition (from 125 to 500°C), and degradation of the remaining lignin (above 500°C). In simple words, biomass produces char, condensable volatiles and tar, and gaseous products during pyrolysis. Char is mainly carbon, and it follows reactions 1 to 7 during gasification. All of the volatiles and some tars are thermally cracked and broken down into simple gaseous products during gasification. The remaining tar and some alkali minerals leave with the product gases. Kumar et al. [22], like many others, presented the complex biomass gasification process in a single equation:

$$CH_xO_yN_zS_s + \text{Air} (79\% \ N_2 \text{ and } 21\% \ O_2) + H_2O \text{ (steam)}$$
$$= CH_4 + CO + H_2 + H_2O \text{ (unreacted steam)}$$
$$+ C \text{ (Char)} + \text{Ash} + \text{Tar}.$$
$$(8)$$

While many researchers mentioned synergy of cogasification of coal and biomass, Pan et al. [16] presented a simplified cogasification reaction scheme. The backbone of this reaction scheme is that both coal and biomass undergo pyrolysis without interaction before entering into the gasification reactions. During the pyrolysis, complete de-volatilization of coal and biomass takes place, and condensable volatiles as well as tar rise along with air/steam away from the gasification zone leaving char behind. These volatile products never get a second chance to come in contact with fresh air/steam. Since methane and ethylene formation does not take place at atmospheric pressure, their presence in the product syngas is the result of pyrolysis. In the next step, gasification of the remaining char and residual coal takes place to form CO, CO_2, H_2, and other gases. The reaction scheme presented by Pan et al. [16] does not explain the synergic effect of cogasification which needs further investigation.

There are various factors which influence the cogasification process and the composition of the product gas. These factors include type of gasifier, gasification temperature, flow rates of coal-biomass mixtures and oxidizing agents (air and/or steam), type and amount of catalysts, proportion of biomass in the coal-biomass mixture, and the properties and type of biomass [14, 18, 21].

4.1. Gasifier Type. Both fixed bed and fluidized bed gasifiers have been used in cogasification of biomass with coal. Kumabe et al. [14] used a downdraft fixed-bed gasifier to study cogasification of Mulia coal and Japanese cedar biomass mixtures at 900°C; however, Pan et al. [16] and Vélez et al. [15] attempted cogasification on biomass and coal in fluidized bed gasifiers. Vélez et al. [15] gasified mixtures of biomass (saw dust, rice husk, and coffee husk) and coal in a fluidized bed gasifier at 1000°C. Vélez et al. [15] reported two operational problems. The first problem was defluidization of the fluidized bed gasifier caused due to agglomeration of low melting point ash present in the biomass. The second problem was clogging of the downstream pipes due to excessive tar accumulation.

Collot et al. [17] studied cogasification and co-pyrolysis of birch wood and coal in a fixed bed, possibly an updraft, as well as fluidized bed gasifiers. A major difference between fixed bed and fluidized bed reactors was that the product gas produced from fluidized bed gasification had 4.0 to 6.0% (by weight) tar content; however, the fixed bed reactor gave tar yields ranging from 25.5 to 26.1% (by weight) for cogasification of coal and silver birch wood mixtures (1 : 1 ratio by wt) at 1000°C temperature, 20 bar pressure, and 60 second holding time.

5. Factors Effecting the Cogasification Process

5.1. Feedstock Properties

5.1.1. Type of Biomass. Lignocellulosic biomass is mainly composed of several chemical constituents: cellulose and hemicellulose (60–80% dry basis), lignin (10–25%), and some extractives and minerals [29]. The proportion of these chemical species greatly influences the composition of the gasification products. In a gasification study, Hanaoka et al. [10] reported 97.7%, 92.2%, and 52.8% carbon conversion efficiencies for cellulose, xylan (hemicelluloses), and lignin, respectively. While the gasification products were similar for lignin and xylan, cellulose produced high amounts of CO_2 (carbon dioxide) and CH_4 (methane) in the product gas compared to lignin and xylan. In another study, Yang et al. [30] reported that lignin contributed to high H_2 (hydrogen) yields in the gasification products, almost four times higher than cellulose. Kezhong et al. [21] used two types of biomass, pine sawdust and rice straw, along with Shenmu coal. When 20% of each biomass (oven dried for 20 hours at 90°C) with 80% coal was gasified, H_2 composition in syngas gas increased from 17.66% for pine sawdust to that of 21.96% for rice straw. Three types of different biomass, rice husk, sawdust, and coffee husk, were used by Vélez et al. [15]. A mixture of 6% of coffee husk with subbituminous coal produced 14%, 8%, and 8.2% of H_2, CO_2, and CO, respectively. A mixture of sawdust with coal produced syngas composition of 10.7%, 10%, and 11.8% H_2, CO_2, and CO, respectively, and a mixture of coal and 6% of rice husk produced syngas composition containing 11.4% of H_2, 9.3% of CO_2, and 6.0% of CO. These results suggest that the type of biomass selected during the cogasification influences the product gas composition.

5.1.2. Proportion of Biomass in Coal-Biomass Mixtures. The proportion of biomass in the cogasification process influences product gas composition [14, 15]. Vélez et al. [15] prepared mixtures of coal and raw biomass on a weight basis whereas Kumabe et al. [14] mixed coal and raw biomass on a molar carbon basis. Mulia coal and Japanese cedar biomass were mixed and gasified in a downward draft fixed bed gasifier [14] at 1173 K temperature. The mixtures were prepared using varying proportions of biomass from 0 to 1 on a molar carbon basis and the influence of the amount of biomass was studied with respect to the molar ratio of H_2, CO, and CO_2 in the product gas. The study reported that the gas composition varied with variation in biomass ratio. As the biomass ratio increased from 0 to 1, H_2 composition decreased from 47.9 to 37.5 vol% and CO_2 content increased from 26.1 to 33.7 vol%. The other gas species like CO (22.1–23.9 vol%), CH_4 (2.6–4.6 vol%) and others (0.8–2.9 vol%) were independent of biomass ratio. The molar ratios of H_2/CO and H_2/CO_2 decreased from 2 to 1 with increase in biomass ratio from 1 to 2. Kezhong et al. [21] reported increase in hydrogen yield from 17.66% to 19.30% and CO_2 yield from 19.07% to 20.22% when the biomass ratio was increased to 20% to 33% during cogasification.

In the study conducted by Vélez et al. [15], the mixtures of 6 and 15% raw biomass (saw dust, rice husk, and coffee husk) with subbituminous coal were gasified in preheated steam and air. The authors concluded that the high proportion of biomass in the mixture increased hydrogen content in the product gas (up to 15%) but significantly decreased the energy efficiency of the process. Beside proportion of biomass, cogasification also depends on the type of coal used in the mixtures [16]. In a fluidized bed cogasification study of pine wood and two types of coals (low-grade coal and refuse coal), Pan et al. [16] reported that a minimum of 20% pine chip (by weight) for the low-grade coal and 40% pine chip (by weight) for the refuse coal were recommended for cogasification. Similar studies are required for forest residues and coal to gather region-specific experimental data.

5.1.3. Ash Content. The presence of ash in the gasification fuel is not good for fluidized bed gasification. Vélez et al. [15] mentioned that the low melting point of ash present in woody biomass led to agglomeration which caused defluidization problems. The ash caused sintering, deposition, and corrosion of the gasifier construction metal. Biomass containing alkali oxides and salts with ash content above 5% causes clinkering/slagging problems [25]. On the other hand, gasification was improved by adding wood waste with a low-grade coal, having an ash content of 32%. The improvement was due to the high volatiles, the low ash content, and the low sulfur in biomass which counterbalanced the negative effects of the high sulfur present in the coal [18].

It is very important to study the melting of biomass ash, its chemistry within the gasification bed (no bed, silica/sand, or calcium bed), and the fate of alkali metals when using fluidized bed gasifiers.

5.2. Air and Steam Flow Rate.

When air and steam are used as gasifying agents, their accurate flow rates not only create correct stoichiometric gasification conditions but also provide sufficient reaction time, also called residence time, for heavy-molecular-weight volatiles and tar particles to break down into gaseous species. The terms equivalence ratio (ER) and superficial velocity (SV) are used to define air flow rate. ER is defined as the ratio of actual air flow to the air flow required for complete stoichiometric combustion of the gasification feedstock [21]. The term SV is defined as the ratio of actual air flow to the cross-sectional area of the empty gasifier which compensates for the gasifier dimensions. The amount of air supplied to the gasifier determines the degree of combustion and in turn the temperature of the combustion zone for a directly heated gasifier. However, excessive air might provide high conversion, but it will produce syngas with high CO_2 concentration and low calorific value.

In a cogasification study, Ponzio et al. [31] observed that high ER of 0.25 produced significantly higher yield for all the gases than low ER of 0.19. Similar results are also reported by Gil et al. [32] for gasification of pine wood chips. While studying the influence of particle size and reactor geometry in a fluidized bed gasification of coal and coal-derived char, Tomeczek et al. [33] observed that char required more
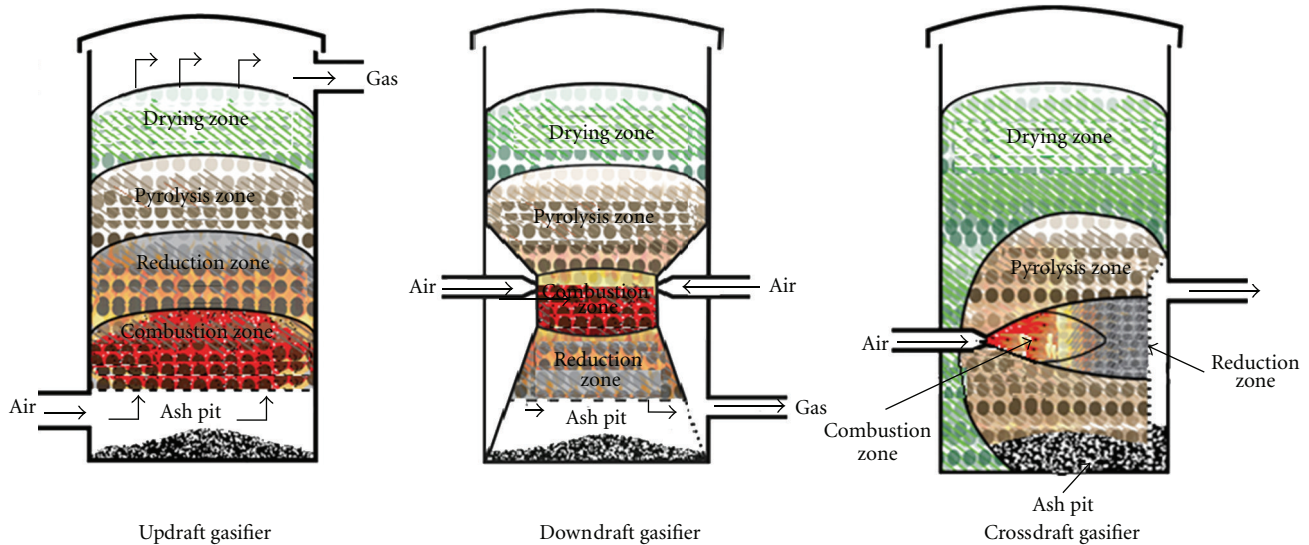
FIGURE 2: Different zones of gasification depending upon the types of gasifier. Image source: http://gekgasifier.com/gasification-basics/gasifier-types/.

residence time than coal to produce product gas of the similar calorific value. Pan et al. [16] observed that the superficial velocities of 0.76–1.45 m/s were too high or in other words residence times 1.7–3.5 s were too low, to achieve water-gas shift reaction equilibrium conditions. Kumabe et al. [14] used commercial Outokumpu HSC Chemistry 5.11 chemical equilibrium calculation software and determined that the air-fuel (O_2/C) of 0.5 mol/mol and steam ratio (H_2O/C) of 3 mol/mol of feed carbon were suitable to produce syngas favorable for synthesis of liquid fuels. Addition of steam favors the water-gas shift reaction and formation of hydrogen during gasification at high temperatures (750–800°C). Steam has also been used by some other researchers in the cogasification process [15, 16, 31, 34]. Vélez et al. [15] observed that a high steam-to-biomass ratio improved hydrogen formation as carbon present in biomass/coal preferred the water-gas and water-gas shift reactions. Ponzio et al. [31] observed a large amount of unreacted steam upon increasing the steam-to-feed ratio more than 53%. Pan et al. [34] used a steam-to-air ratio of 0.55 in their experiments. Kehzong et al. [21] found that when ER ratio was increased from 0.30 to 0.42, the total gas yield increased from 1.75 to 1.94 m³/kg fuel however, the syngas gas yield decreased from 0.98 to 0.93 m³/kg fuel at normal conditions of temperature and pressure, since more oxygen was provided for combustion. Similar results were obtained by Pinto et al. [18] upon cogasification of a coal and pine mixture.

5.3. Gasifier Temperature Profile. The temperature profile along the gasifier greatly influences the product gas composition and hence the calorific value of syngas, by affecting reaction chemistry of gasification (reactions shown by equations 1 to 7). Vélez et al. [15] observed that in the temperature range between 810°C and 850°C, the water-gas shift reaction had a strong role in increasing the hydrogen concentration in the syngas. The reaction also produced a maximum amount

of CO_2 at 820°C. At 850°C, the Boudouard reaction dominated and consumed CO_2 produced through the water-gas shift reaction thereby increased the CO concentration in the product gas. Pan et al. [16] mentioned that attention must be given on the temperature profile to be maintained along the reactor during the design stage. Pan et al. [16] recommended considering long temperature zones for partial oxidation and water gas reactions because these reactions are very slow. In the updraft gasifier, the reactor might be divided into three main zones: the combustion zone at the bottom, the reduction zone in the middle, and the pyrolysis zone at the top. The location of these zones varies with the type of gasifier (Figure 2).

Pan et al. [16] maintained the average temperature between 840°C and 910°C during the cogasification experiments. High temperature in the reduction zone (above 850°C to 900°C) reduces the tar content in the product gas; however, high temperature in the combustion zone might cause sintering problems and defluidization of the bed [22, 34, 35]. Vélez et al. [15] maintained the maximum gasification temperature below 1000°C to avoid sintering. Pinto et al. [18] observed that methane and hydrocarbons were decreased by 30 and 63%, respectively, while H_2 concentration was increased by 70%, when temperature was increased from 750°C to 890°C. In the presence of steam flow rate of 5 kg/h steam and a gasification temperature at 890°C, H_2 (39.8%), CO (17.3%), CO_2 (20.4%), CH_4 (14.9%), and C_nH_m 7.6% (v/v) were produced. Pinto and colleagues recommended that a temperature range of 850 to 900°C should be used for cogasification of coal and pine. The temperature profile inside the directly heated cogasification reactor is also influenced by the proportion of biomass in the coal-biomass mixtures. Pan et al. [16] observed that the average temperature of the fluidized bed gasifier dropped by approximately 60°C when the proportion of pine chip was increased from 20 to 100% in the mixtures. Hence, the temperature profile is

specific to a particular coal-biomass mixture and the type of biomass.

5.4. Catalyst. The use of appropriate catalysts not only reduces reaction temperature but also improves the gasification rates. In addition, catalysts also reduce tar formation. Several studies reported the influence of a catalyst on biomass gasification [6, 35–39]. Lv et al. [35] and Tanaka et al. [39] fed mixture of feedstock and catalyst into the reactor of the gasifier. In a cogasification study performed on coal to assess the influence of switchgrass ash, Brown et al. [40] observed that addition of switchgrass ash to coal increased coal gasification by eightfold. Tanaka et al. [39] observed that NiO/Al_2O_3 catalyst produced product gas with H_2/CO ratio of 2, suitable for methanol synthesis, from the gasification of spruce and hemlock wood sawdust. Lv et al. [35] reported that H_2/CO ratio as high as 4.45 can be achieved by using dolomite and nickel-based catalysts. Rapagna et al. [6] observed that using dolomite or olivine catalyst as a bed material increased gasification by 50% and reduced tar yields by 20 times compared to sand. Asadullah et al. [36, 37] achieved negligible tar formation using $Rh/CeO_2/SiO_2$ catalyst in low-temperature gasification. Aznar et al. [41] observed that when the small pine wood chips were gasified in a nickel-based catalytic fluidized bed reactor with steam-O_2 mixtures followed by high-temperature (ICI 15-5 and BASF K6-11, 350–480°C) and low-temperature (BASF K3-110, 200–260°C) CO-shift reactors, an exit gas with 73 vol% of H_2 (dry basis) was obtained.

In a study of the cogasification of Puertollano coal mixed with pine, petcoke, and polyethylene (PE), Pinto et al. [42] found that the use of dolomite catalyst helped to reduce H_2S and to retain sulfur in solid phase by more than 90%. It also reduced the formation of gaseous chlorine. Dolomite as a catalyst was better than that of Ni-dolomite and G72-D (Zinc oxide) in terms of sulfur and chlorine retention. Catalysts have proven effects on gasification and quality of syngas.

6. Downstream Processing

Following upstream processing and gasification to produce the product fuel gas, it is very important to perform downstream processing of syngas such as cleaning particulate matter, alkali, nitrogen, and sulfur compounds and tar removal to produce a clean gas as required by following applications.

6.1. Particulate Matter Removal. Product gas particulate matter is mainly ash and char particles, and its quantity depends upon the type of gasifier [25]. Conventional cyclone separators can remove particles above 10 μm; however, some type of filtering device must be used to remove particles smaller than 10 μm. Some filters like ceramic filters, wet scrubbers, bag filters, and packed bed filters are 99.8% effective. All the filters which work below 450°C are clogged due to tar deposition [25]. Some ceramic filters can operate as high as 700°C and can be very effective for hot gas cleaning. Vélez et al. [15] used two cyclones connected in series to remove particles down to 5 μm in size from the product gas of

cogasification. Pan et al. [16] used two cyclones followed by a filter and a condenser cooler for gas cleanup from a fluidized bed cogasification experiment.

6.2. Alkali Removal. Alkali elements (Na, K, Mg, Ca) and S present in the feedstock form oxides and vaporize at high temperatures (above 700°C) during gasification. These alkali oxides condense below 650°C and deposit on the downstream sections of the gasification system causing corrosion. In addition, alkali oxides deactivate catalysts used for tar removal. Salo and Mojtahedi [43] reported that the syngas produced from a pressurized fluidized bed gasification reactor at 850°C had concentrations of 1.2 ppm (by weight) for both Na and K compared to 0.05 ppm for the product gas produced at 430°C. Zevenhoven-Onderwater et al. [44] showed that a dolomite bed promotes volatilization of alkali components; however, a silica bed tends to bind most alkali released from the biomass by forming low-melting-point alkali silicates. These low-melting-temperature silicates cause problems with bed agglomeration.

Product gas must be cleaned for most end uses. Nitrogen, generally present as ammonia, is removed by wet scrubbing of the cold gas and by destroying ammonia using dolomite, nickel-based, and iron-based catalysts. Sulfur is converted to SO_2 or H_2S during gasification which can be removed using limestone, dolomite, or CaO.

6.3. Tar Removal. Tar consists of high-molecular-weight compounds exiting the gasifier with the product gas. Tar condenses below 450°C on downstream pipe lines, particulate matter filters, and some of it remains in the product gas in the form of a suspended aerosol. The amount of tar formed during the gasification depends upon the type of biomass, the gasification process, and the operating conditions. Most of the processes which utilize product gas require tar-free syngas. There are two ways to produce tar-free syngas. A first method requires improvements in the gasification technologies with optimized gasifier design, operating conditions, and proper selection of catalysts. The second method is to develop high-efficiency tar removal techniques [25].

It has been shown in previous sections that the gasification operating parameters such as biomass type, the gasifier temperature profile, the ER, the type of gasifying agent, and the steam-to-biomass ratio all influence tar content of the product gas. In addition, the use of a catalyst during gasification also reduces the tar content of the product gas. Tanaka et al. [39] observed no tar formation when a NiO_2/Al_2O_3 catalyst was used during gasification of wood. Pan et al. [34] introduced a secondary air injection at 850°C to crack the tar into lower-molecular-weight gaseous compounds. During the experiments, Pan et al. [34] were able to reduce tar concentration from ≥ 3.70 g/m^3 to 0.42 g/m^3.

Several attempts have been made to capture tar during downstream processing of syngas produced from the cogasification process [14, 31, 35]. Kumabe et al. [14] used an anisole of special grade chemicals, manufactured by Wako Pure Chemical Industries, Ltd., to dissolve tar. Ponzio et al. [31] used a solid-phase adsorption method to capture tars

TABLE 1: Summary of research articles on cogasification of coal and biomass.

Source	Type of feedstock	Gasifier type	Gasification conditions	Effect on syngas compositions and comments
Kezhong et al. [21]	(i) Shenmu bituminous coal (ii) Pine saw dust/rice straw	Fluidized bed	(i) Gasification agent—oxygen-rich air-steam (ii) Equivalent ratio (ER) increased from 0.31 to 0.47 (iii) Temperature 948–1026°C (iv) Steam/carbon ratio (F_s/F_c) = 0.83	(i) H_2 and CO decreased (ii) Total gas yield increased (iii) Syngas yield decreased (iv) Smaller ER is favorable to increase Syngas yield
			(i) Steam/carbon ratio (F_s/F_c) increased from 0.26 to 0.88 (ii) Temperature 921–1033°C (iii) Equivalent ratio (ER) = 0.4	(i) Bed temperature decreased (1033 to 921°C) (ii) H_2 and CO first increased and then decreased (iii) Steam/carbon ratio of 0.5 is preferred
			(i) Biomass/coal ratio increased from 0 to 33% (ii) Equivalent ratio (ER) = 0.34 (iii) Steam/carbon ratio (F_s/F_c) = 0.77 (iv) Temperature: 912–976°C	(i) Bed temperature increased (912 to 976°C) (ii) H_2 increased and CO decreased (iii) Slight decrease in Syngas yield
Pinto et al. [18]	(i) 60% coal (ii) 20% pine (iii) 20% polyethylene	Fluidized bed	(i) Temperature increased from 750 to 890°C (ii) Gasification agent—air, steam, and mixture of both (iii) Steam input rate = 5.0 Kg/h (iv) Air input rate = 4.4 Kg/h	(i) CO_2 decreased and H_2 increased (ii) Not much effect on char (iii) Energy conversion increased (iv) Gas composition (v/v) at 890°C: H_2: 39.4%, CO: 17.3%, CO_2: 20.4%, CH_4: 14.9% and C_nH_m—7.6%
			(i) (Oxygen/oxygen + steam) ratio increased from 0.02 to 0.28 (ii) Temperature: 850°C (iii) Feedstock input rate = 5.0 Kg/h	(i) 15% reduction in H_2 production (ii) 38% and 53% reduction in CH_4 and hydrocarbons (iii) Total gas yield decreased
			(i) (Steam + O_2)/fuel ratio increased from 1.1 to 1.9 (ii) Air input rate = 4.4 Kg/h (iii) Steam input rate = 5 Kg/h	(i) H_2 and CO_2 first increased and then decreased (ii) CO and CH_4 first decreased and then increased (iii) (Steam + O_2)/fuel ratio of 1.3–1.5 is preferred
Kumabe et al. [14]	(i) Mulia coal (ii) Japanese cedar	Fixed bed downdraft	(i) Air-steam gasification (ii) Biomass ratio increased from 0 to 1	(i) H_2 decreased and CO_2 increased (ii) Cold gas efficiency increased (iii) No effect on CH_4 concentration

TABLE 1: Continued.

Source	Type of feedstock	Gasifier type	Gasification conditions	Effect on syngas compositions and comments
Vélez et al. [15]	(i) Columbian coal (ii) Coffee husk (iii) Sawdust (iv) Rice husk	Fluidized bed	(i) Air-steam gasification (ii) Biomass ratio was increased from 6% to 15% (iii) Temperature <1000°C (iv) Steam/fuel ratio was increased	(i) Bed temperature decreased by 30°C with 15% biomass (ii) Energy efficiency decreased (iii) High H_2 concentration was obtained with increase in biomass ratio as well as steam/fuel ratio
Pan et al. [16]	(i) Pine chips (ii) Black coal (iii) Sabero coal	Fluidized bed gasifier	(i) Biomass ratio was increased: 0%, 25%, 40%, and 100% (ii) Air-steam gasification (iii) Temperature = 840–910°C	(i) CO increased (ii) H_2 first increased up to 25% of biomass and then decreased (iii) Overall thermal efficiency increased (40% to 68%) (iv) Carbon conversion efficiency increased (63% to 83.4%)
Couhert et al. [28]	(i) Beachwood (ii) Torrefied beachwood at 240°C (iii) Torrefied beachwood at 260°C	Entrained flow reactor	(i) Feedstock: beachwood and torrefied beachwood (ii) Temperature = 1200 and 1400°C	(i) CO_2 remained same (ii) H_2 was increased by 7% with torrefied wood (iii) CO was increased by 20% with torrefied wood

from the product gas. Lv et al. [35] used dichloromethane cooled to $-10°C$ to condense and collect tar.

7. Environmental Benefits

Greenhouse emissions from coal gasification are higher than that from biomass gasification [45]. This could be due to the high carbon content and low volatile percentage in coal [14]. For measuring greenhouse emissions, the GHGI (greenhouse gas emission index) is used, which is defined as the lifecycle greenhouse gas emission associated with the energy products divided by the lifecycle greenhouse gas emissions associated with the fossil-fuel-derived products displaced [45]. In a study conducted to produce electricity and FT (Fisher Tropsch) liquids from coal and biomass, Lui et al. [45] found that GHGI was 1.71 for coal gasification which came down to 0.96 when a mixture of 40% biomass-60% coal was used as feedstock. From these results, it can be concluded that using biomass with coal is beneficial for the environment in terms of greenhouse gas emissions.

Cogasification combined with Fisher-Tropsch technology is used to produce liquids from coal and biomass. CBTL (Coal-Biomass to liquids) helps to reduce GHG emissions as compared to petroleum-derived diesel. NETL (National Energy Technology Laboratory) reported that the use of 30% switchgrass (Biomass) with coal for producing diesel (CBTL) with carbon capture and storage technology (CCS) produced 63% less GHG emission compared to a fossil-derived diesel. GHG emission can further be decreased up to 75% by using more aggressive capturing technique of auto-thermal reformer in CCS. This technique is economically competitive with fossil-based diesel if the cost of crude oil remains somewhere between $100 and $120/bbl [46].

8. Summary

A review of up-stream, gasification, and downstream processing is presented in this paper. A summary of literature review has also been presented in Table 1. Composition of product gas is effected by the various up-stream and downstream processes and other gasification parameters. Feedstock properties like particle size and moisture content of the biomass feed should be kept in range of 0.5 to 1.0 mm and 10–15%, respectively. Upstreaming processes like torrefaction of biomass help to increase H_2 and CO yield. The type of gasifier is selected according to the feedstock properties and the desired utilization of the syngas. If syngas is used for electric generation then a downdraft gasifier should be used because it releases gas at high temperature with low impurities and hence causes fewer side effects on the engine. Beside the gasifier, the type of gasifying agent is also important. The use of steam as a gasifying agent assists the water-gas shift reaction and produces H_2-rich syngas. In contrast, if air is used, then less H_2 is produced. Also, the use of catalysts affects syngas production. Dolomite catalysts help in increasing the gasification rate along with reducing the sulfur and chlorine. Once gas is produced, it contains impurities like particulate matter, alkali, and tars. These impurities must

be removed before using the product gas. Particulate matter can be removed by attaching a cyclone separator at the gas exit, while alkalis and tars can be removed by using catalysts and secondary air injection in the gasifier system which helps in combustion of tars.

Despite much research in this field, cogasification of forest logging residue with coal has not yet been fully explored. The tar evolution profile from the cogasification of forest residue and coal requires further investigation to customize the design of the gasifier, its operating conditions, and tar removal system. Along with this, the use of an entrained flow gasifier for the cogasification of coal and biomass can also be a research opportunity for the future because different types of feedstock can be used in it. Moreover, it has other advantages like uniform temperature profile inside the reaction zone, short reactor residence time, and high carbon conversions.

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