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# Exploring Novel Biomass Feedstocks in Downdraft Gasification Systems : A Technical Review

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**ABSTRACT**

This review paper provides a comprehensive analysis of the current advancements in biomass gasification, a prominent method for biomass-based energy generation. Biomass gasification involves the thermo-chemical conversion of organic materials into syngas, with its efficiency influenced by various factors such as fuel type, reactor design, and operational parameters. The paper systematically categorizes and evaluates recent research in gasification modeling, focusing on key criteria like gasifier types, feedstock characteristics, modeling approaches, and performance parameters. By comparing different modeling techniques and their outcomes, this review aims to offer valuable insights for researchers, engineers, and policymakers involved in optimizing gasification systems. The analysis highlights the importance of computational models in reducing the need for costly and time-intensive experiments, and provides a framework for future research directions in the field of biomass gasification.

**Keywords :** Downdraft, Feedstock, Gasifier, Biomass.

**Introduction:**

As the world grapples with the challenges posed by dangerous atmospheric deviations and climate change, significant research and development have focused on biomass as an alternative to fossil fuels [1]. The abundant availability of biomass has been widely acknowledged, along with its potential to provide significantly larger amounts of useful energy with fewer environmental impacts compared to non-renewable sources. Biomass can be converted into commercial products through biological or thermochemical processes. However, the biological conversion of low-value lignocellulose biomass still faces challenges in terms of cost-effectiveness and efficiency. The three primary thermochemical conversion methods are combustion, pyrolysis, and gasification. Traditionally, biomass is combusted to generate heat and power in industrial processes [2]. However, the net efficiency of power generation from biomass combustion is typically quite low, ranging from 20% to 40%. In existing combustion systems, biomass co-firing is usually limited to 5-10% of the total feedstock due to concerns about clogging coal feed systems [3].

Pyrolysis converts biomass into bio-oil in the absence of oxygen (O2). However, the limited applications and challenges in the downstream processing of bio-oil have restricted the widespread adoption of biomass pyrolysis technology. Gasification, on the other hand, converts biomass through partial oxidation into a gaseous mixture, along with small amounts of char and condensable compounds [4]. It is considered one of the most efficient methods for harnessing the energy stored in biomass and is increasingly regarded as one of the best options for recycling solid waste. There have been ongoing efforts to demystify the complex nature of gasification. It is now timely to review gasification process modeling to emphasize the role of gasification models. This review aims to evaluate and analyze various biomass gasification models developed by different researchers [3-5].

**Principle and Technologies**

Gasification is a process of partial thermal oxidation, which produces a high proportion of gaseous products (such as CO2, water, carbon monoxide, hydrogen, and gaseous hydrocarbons), along with small amounts of char (solid residue), ash, and condensable compounds like tars and oils [6]. During the gasification process, steam, air, or oxygen is supplied as an oxidizing agent. The resulting gas can be standardized for quality and is easier and more versatile to use compared to raw biomass (e.g., it can be used to power gas engines and turbines, or serve as a chemical feedstock for the production of liquid fuels) [7]. Gasification adds value to low- or negative-value feedstocks by converting them into desirable fuels and products. The chemistry behind biomass gasification is highly complex. Broadly, the gasification process consists of the following stages [9-12-15]:

Drying: In this initial stage, the moisture content of the biomass is reduced. Typically, biomass has a moisture content ranging from 5% to 35%. Drying occurs at around 100–200°C, reducing the moisture content to less than 5%.

Devolatilization (Pyrolysis): This stage involves the thermal decomposition of biomass in the absence of oxygen or air. During this process, the volatile matter in the biomass is reduced, resulting in the release of hydrocarbon gases and the formation of solid charcoal. At sufficiently low temperatures, these hydrocarbon gases can condense to form liquid tars.

Oxidation: In this phase, the carbonized biomass reacts with oxygen in the air, leading to the formation of CO2. Any hydrogen present in the biomass is also oxidized, producing water. The oxidation of carbon and hydrogen releases a significant amount of heat. If oxygen is available in sub-stoichiometric amounts, partial oxidation of carbon may occur, resulting in the production of carbon monoxide.

Reduction: In the absence or sub-stoichiometric presence of oxygen, several reduction reactions take place within the temperature range of 800–1000°C. These reactions are mostly endothermic. The key reactions during this stage are as follows:

The gasification process transforms biomass into a versatile energy source, unlocking its potential to be used in various applications, from fuel production to electricity generation.

These responses are generally endothermic.

The principle responses in this class are as per the following:

Water reaction

$$C + H_2O = CO + H_2 - 131.4 \text{ kJ/gmol} \quad (1)$$

Bounder reaction

$$C + CO_2 = 2CO - 172.6 \text{ kJ/gmol} \quad (2)$$

Shift reaction

$$CO_2 + H_2 = CO + H_2O - 42 \text{ kJ/gmol} \quad (3)$$

Methane reaction

$$C + 2H_2 = CH_4 + 75 \text{ kJ/gmol} \quad (4)$$

Gasification reactor designs have been studied for over a century, leading to the development of several configurations at both small and large scales. These reactors can be classified in various ways:

1. By Gasifying Agent:
    - Air-blown gasifier
    - Oxygen gasifier
    - Steam gasifier
2. By Heat Source:
    - Auto-thermal or direct gasifier: Heat is provided by the partial combustion of biomass.
    - Allothermal or indirect gasifier: Heat is supplied from an external source, usually via a heat exchanger or an indirect process.
3. By Gasifier Pressure:
    - Atmospheric gasifier
    - Pressurized gasifier
4. By Reactor Design:
    - Fixed-bed Gasifiers (updraft, downdraft, cross-draft, and open-core) [8]: In these reactors, a bed of solid fuel particles interacts with the gasifying agent, which moves either upward (updraft), downward (downdraft), or horizontally (cross-draft) through the bed. Fixed-bed gasifiers are the simplest type, consisting of a cylindrical chamber for fuel and gasifying media, with units for fuel feeding, ash removal, and gas output. During gasification, the fuel bed slowly descends as the process progresses. Fixed-bed gasifiers are easy to construct and generally exhibit high carbon conversion rates, extended solid residence time, low gas velocity, and low ash carryover.
    - Fluidized-bed Gasifiers (bubbling, circulating, and twin-bed): In this design, the gasifying agent is introduced at high enough velocities to keep solid particles suspended, creating a fluidized state. Fuel particles are introduced at the bottom of the reactor, mix rapidly with the bed material, and are quickly heated to the bed's operating temperature. This process leads to rapid pyrolysis, producing a mixture with a large proportion of gaseous materials. Further gasification and tar reforming reactions occur in the gas phase. Twin-bed gasification involves two separate fluidized-bed reactors: one for biomass gasification with steam, and another for combustion of the remaining char with air. Heat generated in the second reactor is transferred to the gasification reactor via the bed material, typically sand, with separate exit paths for the vent gas and the product gas [10].
    - Entrained-flow Gasifiers: These reactors are often used for coal gasification due to their ability to process slurry-fed biomass. They operate at high temperatures, pressures, and capacities, with short residence times [11]. This makes them suitable for handling solid fuels in indirect gasification mode, reducing the cost of feeding solid fuel at high pressures.
    - Stage Gasification: This design separates pyrolysis, oxidation, and reduction zones physically within the reactor. The downdraft gasifier is a well-established innovation with specific fuel requirements suitable for low-moisture biomass. It generates a moderate calorific value producer gas with low tar and ash content, exhibiting high exit gas temperatures and optimized for capacities of 20 to 200 kW. While it achieves high carbon conversion and extended

residence time for solids, its scale-up potential is limited to around 250 kW.In contrast, the bubbling fluidized bed gasifier offers greater fuel flexibility and operates efficiently at lower loads, characterized by ease of operation and good temperature control. It produces a moderate heating value gas with low tar and some particulate content, maintaining high conversion efficiency suitable for larger-scale capacities up to 1 MW or more.The entrained-flow bed gasifier features a complex design with specific particle size requirements, necessitating costly feed preparation. It operates at high temperatures, achieving excellent gas quality and conversion efficiency, making it suitable for high-capacity operations exceeding 1 MW and demonstrating significant scale-up potential [12-13-14-16-17].

**Literature Survey**

Authors investigated the performance of a gasifier fed by different feedstocks, including rice husk, sawdust, and their mixture. The study found that the gasification efficiency was highest for the sawdust feedstock, with a syngas yield of 2.6 $Nm^3/kg$ of biomass. The syngas composition was 19% $H_2$, 20% CO, and 2% $CH_4$, with an LHV of 5 $MJ/Nm^3$. Table 1 and 2 presents the proximate analysis, ultimate analysis, higher heating value (HHV), and lower heating value (LHV) of the rice husk and sawdust used [16].

Table 1 Proximate Analysis [16]

| Component | Rice Husk | Sawdust | ASTM Standards |
|---|---|---|---|
| Fixed Carbon (%) | 12.83 | 13.29 | D 3172 |
| Volatile Matter (%) | 56.20 | 71.48 | D 3175 |
| Ash (%) | 21.17 | 1.97 | D 3174 |
| Moisture Content (%) | 9.80 | 13.26 | D 3173 |

Table 2 Ultimate Analysis [16]

| Component | Rice Husk | Sawdust | ASTM Standards |
|---|---|---|---|
| Carbon (C, %) | 34.05 | 44.99 | D 5373 |
| Hydrogen (H, %) | 5.35 | 6.68 | D 5373 |
| Oxygen (O, %) | 39.14 | 45.62 | D 3176 |
| Nitrogen (N, %) | 0.17 | - | D 5373 |
| Sulfur (S, %) | 0.12 | 0.74 | D 4239 |
| Higher Heating Value (HHV, MJ/KG) | 13.39 | 17.775 | |
| Lower Heating Value (LHV, MJ/KG) | 12.083 | 15.919 | |

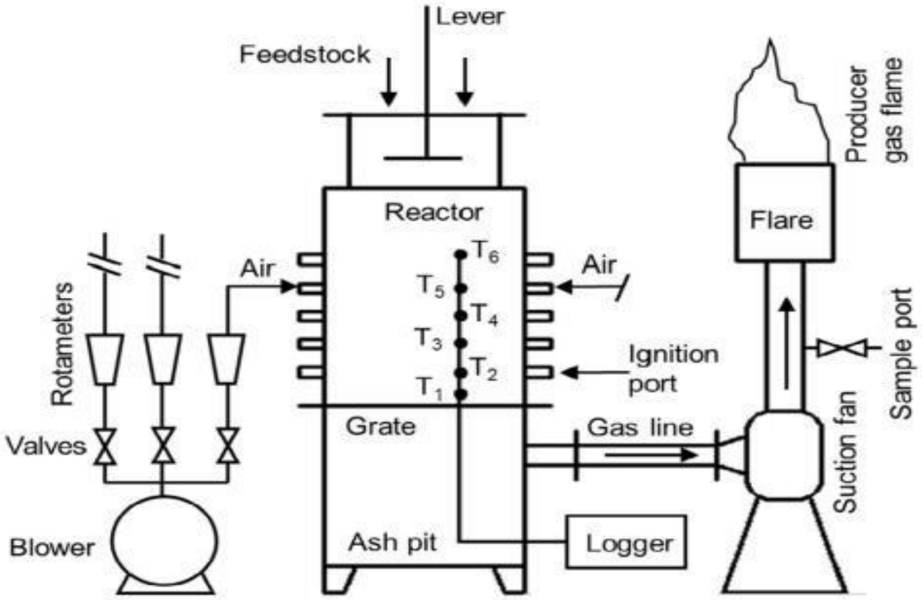

Figure 1. Schematic Diagram of Experiment Setup [16]

The study assesses the efficacy of an automated multi-fuel downdraft gasifier for energy generation. The principal results demonstrate that the gasifier attained a significant conversion efficiency, producing a syngas output of 2.5 $Nm^3/kg$ of biomass. The syngas included 21% $H_2$, 19% CO, and 2% $CH_4$, with a lower heating value (LHV) of 5.2 $MJ/Nm^3$ [17].

Authors examined the efficacy of biomass gasification in a dual air stage downdraft reactor. The dual air stage design seeks to optimize the gasification process by enhancing air circulation inside the reactor, hence diminishing tar production and elevating syngas quality. The research indicated that the second air stage markedly enhanced gasification efficiency, yielding a syngas composition of 18% hydrogen ($H_2$), 20% carbon monoxide (CO), and 2% methane ($CH_4$), with a lower heating value (LHV) of 5.1 $MJ/Nm^3$. The decrease in tar concentration was significant, enhancing the syngas's suitability for energy applications [18].

Authors investigated the co-gasification of biomass and high-density polyethylene (HDPE) blends in a downdraft gasifier. The study indicates that co-gasification improves syngas quality and decreases tar production relative to the gasification of biomass in isolation. The syngas generated from the biomass-HDPE blend included 22% $H_2$, 18% CO, and 2.5% $CH_4$, exhibiting a lower heating value (LHV) of 5.3 $MJ/Nm^3$. The research indicates that integrating HDPE into the biomass feedstock enhances the efficiency and yield of the gasification process. [19] .

Authors investigated many feedstocks in a downdraft gasifier, including pine, horse dung, red oak, and cardboard. The reported gasifier efficiencies were 0.8195 for pine, 0.8439 for horse dung, 0.8462 for red oak, and 0.8166 for cardboard. The percentages of hydrogen and methane were as follows: pine (15% $H_2$, 5% $CH_4$), horse dung (20% $H_2$, 3% $CH_4$), red oak (17% $H_2$, 1.5% $CH_4$), and cardboard (11% $H_2$, 3% $CH_4$) [20].

Authors examined a non-woody biomass gasifier with a diameter of 0.3 m and a height of 0.85 m, noting that an increase in the equivalent ratio from 0.18 to 0.41 resulted in elevated temperatures[21].

Authors investigated the impact of operational parameters on gas quality in a downdraft gasifier using a two- stage air supply. The results demonstrate that enhancing the air supply may significantly elevate the quality of the generated syngas. The ideal circumstances produced a syngas composition of 22% $H_2$, 19% CO, and 2% $CH_4$, yielding a lower heating value of 5.2 MJ/Nm³. The study indicates that meticulous regulation of operational parameters is essential for optimizing the efficiency and productivity of gasification systems [22].
Authors discussed the selection, design, and gasification of oil palm fronds using preheated and unheated gasifying air. The study found that preheating the gasifying air enhanced the gasification efficiency and improved the quality of the produced syngas. The syngas composition with preheated air was 20% $H_2$, 18% CO, and 2% $CH_4$, with an LHV of 5 MJ/Nm³. The work highlighted the benefits of preheating the gasifying air to optimize the gasification process and improve energy output [23]. Table 2 compares gas compositions from unheated and preheated air, showing higher hydrogen and carbon monoxide percentages with preheated air, and a higher heating value.

Table 3 presents feed rates and equivalent ratios in a three-stage air gasification process. Table 4 lists the chemical and physical properties of different biomass pellets, with DDGS and Miscanthus pellets having varied carbon, nitrogen, moisture content, ash, and heating values.

Table 3 : Gas Composition from Unheated vs. Preheated Air[21]

| Gas Component | Unheated (%) | Preheated (%) |
|---|---|---|
| Hydrogen | 8.47 | 10.53 |
| Carbon Monoxide | 22.87 | 24.94 |
| Methane | 2.03 | 2.03 |
| Higher Heating Value | 4.66 MJ/Nm³ | 5.31 MJ/Nm³ |

Table 4 : Feed Rate and Equivalent Ratio in Three-Stage Air Gasification[24]

| Stage | 1st Stage | 2nd Stage | 3rd Stage |
|---|---|---|---|
| Feed Rate (kg/hr) | 7.5 | 5.8 | 6.7 |
| Equivalent Ratio | 0.18 | 0.27 | 0.27 |

Table 5 : Chemical and Physical Properties of Pellets [26]

| Property | DDGS Pellets | Miscanthus Pellets | Simple Miscanthus Pellets |
|---|---|---|---|
| C (%) | 44.18 | 44.59 | 41.51 |
| H (%) | 5.9 | 5.12 | 4.85 |
| N (%) | 4.95 | 0.4 | 0.4 |
| O (%) | 32.95 | 36.89 | 35.68 |
| S (%) | 0.52 | 0.01 | 0.04 |
| Moisture Content (%) | 7.4 | 10.18 | 11.58 |

| | | | |
|---|---|---|---|
| Ash (%) | 3.9 | 2.8 | 6.5 |
| Volatile Matter (%) | 73.2 | 71.1 | 63.9 |
| Fixed Carbon (%) | 15.5 | 15.9 | 18 |
| HHV (MJ/kg) | 18.6 | 18.8 | 16.2 |
| LHV (MJ/kg) | 17.2 | 17.5 | 14.9 |
| Pellet Size (mm) | 6 | 8 | 7 |
| Bulk Density (kg/m²) | 714.3 | 578.5 | 625 |

Increasing the equivalence ratio (ER) in gasification raises temperatures, enhancing heat release and reducing tar yield. For ER between 0.18 and 0.37, CO and $H_2$ levels first rise, then fall, while $CO_2$ shows the opposite trend. At an ER of 0.25-0.27 and biomass feed rate of 7.5 kg/h, the gasifier reaches optimal conditions with a lower heating value (LHV) of 5400 kJ/m³ and 65% cold gas efficiency. Higher ER further reduces tar yield, but excessive feed rates lower gas quality ($H_2$ and CO) and increase tar output.[24]

The authors studied and evaluated the efficacy of a downdraft biomass gasifier using a mixture of coconut shell and rubber seed shell as feedstock. The work indicated that the amalgamation of these feedstocks enhances gasification efficiency and the quality of syngas. The ideal mixture yielded syngas of 22% $H_2$, 18% CO, and 2% $CH_4$, with a lower heating value of 5.3 MJ/Nm³. The results indicate that using mixed feedstocks may augment the efficacy of biomass gasifiers and boost the sustainability of the gasification process[25].

Authors explored the effect of design and operating parameters on the biomass gasification process in a downdraft fixed bed. Their experimental study revealed that optimal conditions significantly enhanced syngas quality, producing a gas with 21% $H_2$, 19% CO, and 2% $CH_4$, and an LHV of 5.2 MJ/Nm³. The authors highlighted the importance of optimizing both design and operational parameters to improve gasification efficiency[26].

Authors investigated the gasification of different biomass types with air. They demonstrated that biomass type significantly impacted syngas composition and quality, with the best results yielding 20% $H_2$, 18% CO, 2% $CH_4$, and an LHV of 5 MJ/Nm³. The authors emphasized the importance of selecting suitable biomass types to enhance gasification performance.27].

The authors designed and experimentally investigated a 190 kWe biomass fixed bed gasification and polygeneration pilot plant using a double air stage downdraft approach. They found that the double air stage design significantly improved gasification efficiency and syngas quality. Under optimal conditions, the syngas composition reached 22% $H_2$, 19% CO, and 2% $CH_4$, with an LHV of 5.3 MJ/Nm³. The research demonstrated the potential of double air stage designs to enhance the performance of biomass gasification systems [28].

## Conclusion

Forest biomass has significant potential to mitigate greenhouse gas emissions in district energy systems; yet, its implementation is progressing more slowly than expected. Supportive policies and incentives are essential to expedite growth, as shown by Sweden's success with government subsidies. District energy suppliers have to consider forest biomass as a sustainable investment, enabling learning effects to decrease production costs over time. Nonetheless, the rising demand for forest biomass need management to prevent unsustainable harvesting techniques that might jeopardize biodiversity, soil, and water resources. Establishing new norms and regulations is crucial for ensuring sustainable harvesting of forest biomass.

Gasification experiments have shown the potential of numerous feedstocks, including rice husk, sawdust, wood chips, and sewage sludge. An optimal cold gas efficiency of 82.7% was attained by the use of a blend of sewage sludge and wood pellets. Downdraft gasifiers using a dual air supply system enhanced tar conversion and syngas quality, yielding gases with 19.04% CO, 16.78% $H_2$, and 0.89% $CH_4$. Preheated air in palm frond gasification enhanced $H_2$, CO, and the greater heating value. Gasifiers using non-woody biomass had enhanced equivalent ratios, resulting in increased gas output and less tar production. Furthermore, copper slag used as a catalyst in upward gasifiers enhanced gas quality by diminishing emissions of $H_2$, CO, and $CH_4$.

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