https://doi.org/10.3311/PPch.39516

Periodica Polytechnica Chemical Engineering, 69(3), pp. 445–456, 2025

Synergistic Effects of Biomass-polyethylene Co-gasification: A Simulation Approach

Nomadlozi Lucy Khumalo[1], Bilal Patel[1*]

[1] Department of Chemical and Materials Engineering, University of South Africa (UNISA), 28 Pioneer Ave, Florida Park, 1709 Roodepoort, South Africa
[*] Corresponding author, e-mail: patelb@unisa.ac.za

Received: 09 December 2024, Accepted: 07 May 2025, Published online: 30 May 2025

Abstract

A parametric study on syngas production from the co-gasification of biomass and plastic waste using oxygen as the gasifying agent was conducted using an Aspen Plus simulation. The study examined the effect of plastic content and its synergistic interaction with biomass. Key operating parameters, including equivalence ratio (ER) and blend ratios were varied to assess their impact on hydrogen and carbon monoxide concentrations, the H_2/CO ratio, lower heating value (LHV), gas yield (GY), and cold gas efficiency (CGE). Increasing plastic content enhanced H_2 concentration but reduced CO levels. At ER of 0.1, a 75% polyethylene and 25% biomass mixture achieved 56% H_2 while pure biomass yielded 56.4% CO. The highest CO content in the blended feedstock (54.2%) was obtained at ER of 0.22 with 25% PE and 75% biomass. The H_2/CO ratio of 2, ideal for synthetic fuel applications, was achieved at an ER value below 0.4 for 50% and 75% PE mixtures. While the co-gasification improved H_2 production, LHV showed no enhancement, indicating no additional energy benefits from co-gasification. However, the GY exhibited synergy, as co-gasification produced more syngas as ER increased, CGE improved due to synergy, particularly at ER values below 0.4 demonstrating enhanced feedstock conversion efficiency. These findings suggest that co-gasification enhances syngas production and overall quality, making it a highly viable process for improving the efficiency of waste-to-energy technologies. In addition, biomass-polyethylene co-gasification shows potential in improving syngas quality, addressing challenges like low H_2/CO ratios and low LHV, which are common issues in conventional biomass gasification.

Keywords

plastic waste, biomass, oxygen, co-gasification, syngas

1 Introduction

The detrimental environmental effects of relying on fossil fuels to meet energy demands, particularly the significant release of CO_2 and other pollutants, are well documented. This has created an urgent need for more sustainable solutions in the energy sector. Consequently, there is growing demand for reliable, affordable and cleaner alternative energy sources. Biomass, a renewable and carbon-neutral energy resource, is abundantly available, with an estimated global annual production of 1.7 trillion metric tons [1]. As it gains prominence in modern energy systems, biomass is increasingly recognized as a leading option for clean energy. Although biomass utilisation results in some CO_2 emissions, it remains the only renewable carbon source on Earth, making it a viable substitute for fossil fuels [2]. Additionally, unlike other renewable resources, biomass can be converted into various energy carriers, such as biochar, bio-oil, methanol, ethanol, dimethyl ether (DME), biodiesel, and syngas. Biological methods like fermentation and anaerobic digestion, along with thermochemical processes such as pyrolysis, combustion, and gasification, are widely used for the conversion of biomass into energy. Thermochemical methods are often preferred due to their faster conversion rates, higher stoichiometric yields without the need for chemical additives, and the capability to process a variety of wet biomass feedstocks [3]. Among thermochemical techniques, gasification stands out as the most popular due to its higher efficiency scalability, and versatility in handling a range of feedstocks. It generates a gaseous fuel with a high calorific value, making it an ideal choice for energy production and engineering applications [4]. Gasification is a well-established, environmentally friendly, and cost-effective technology for converting solid biomass to syngas [5]. Fig. 1 illustrates the biomass gasification process and technology, highlighting

Cite this article as: Khumalo, N. L., Patel, B. "Synergistic Effects of Biomass-polyethylene Co-gasification: A Simulation Approach", Periodica Polytechnica Chemical Engineering, 69(3), pp. 445–456, 2025. https://doi.org/10.3311/PPch.39516

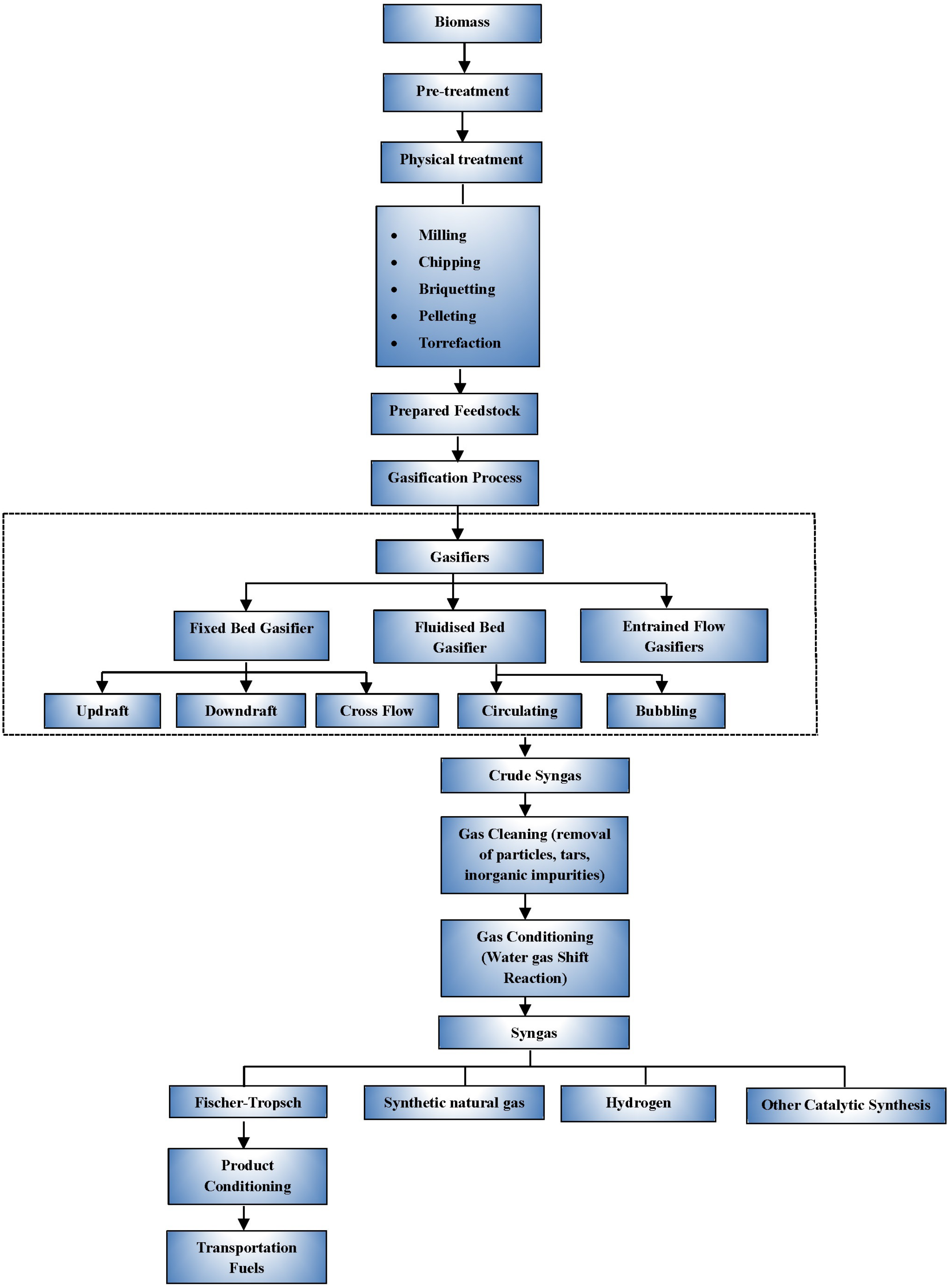

Fig. 1 Flow diagram of the process for gasification

the various syngas generation pathways that depend on different types of gasifiers and their respective operating conditions. As shown in Fig. 2 biomass gasification involves several stages, including drying, pyrolysis, oxidation, and gasification [6]. In the drying stage, biomass is heated to reduce moisture content before undergoing pyrolysis, oxidation, and subsequent gasification.

In the drying stage, the material is exposed to heat at temperature of 150 °C to remove moisture, but no chemical reactions take place at this phase. The drying time is significantly

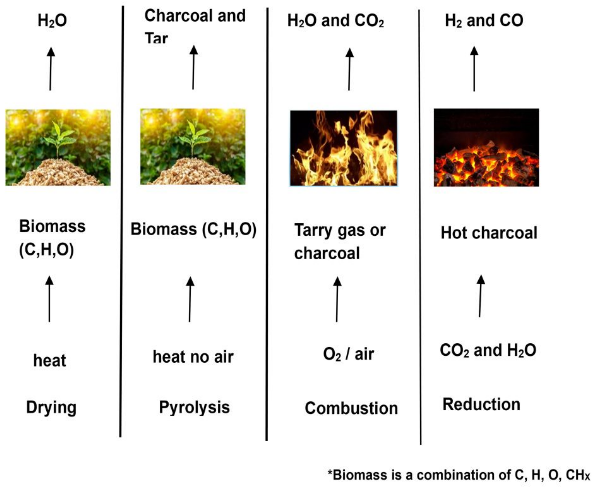

Fig. 2 Biomass gasification process [6]

influenced by factors such as particle size. Larger particles typically require more time because moisture must travel a greater distance to escape from the core of the material [7]. Then, the dried feedstock passes to the pyrolysis stage. In the pyrolysis stage, the solid material undergoes thermal decomposition in the absence of oxygen or air. This process primarily breaks down complex organic substances into simpler molecules, producing gases, liquids (such as tar or bio-oil), and a solid residue (char). The general reaction for pyrolysis can be represented by Eq. (1):

$$\begin{aligned} C_nH_mO_p + \text{heat} \rightarrow\ & \textstyle\sum_{\text{liquids}} C_aH_bO_c + \\ & + \textstyle\sum_{\text{gases}} C_xH_yO_z + \textstyle\sum_{\text{solids}} C \end{aligned} \tag{1}$$

Equation (1) represents the stoichiometric breakdown of the feedstock during pyrolysis, showcasing its transformation into valuable products under specific conditions [8]. The subsequent combustion (oxidation) process is exothermic, releases heat due to the oxidation of carbon and hydrogen in the fuel to form carbon dioxide and water.

The overall combustion reaction can be expressed as:

Complete oxidation:

$$C + O_2 \rightarrow CO_2 + 401.9\ \text{kJ/mol} \tag{2}$$

Partial Oxidation:

$$C + \frac{1}{2}O_2 \rightarrow CO + 241.1\ \text{kJ/mol} \tag{3}$$

This thermal energy is crucial for sustaining the endothermic gasification reaction, where, carbon reacts with a limited supply of oxygen, steam, or carbon dioxide to produce syngas, a mixture consisting primarily of CO and H_2 [9]. This process plays a critical role in converting solid biomass into a versatile gaseous fuel with high calorific value, making it a promising technology for energy applications.

The primary reactions involved in biomass gasification including oxidation, reduction and water-gas reactions, play a crucial role in determining the composition of the produced syngas and the overall efficiency of the gasification process [10]. The following equations, labeled as Eqs. (4) to (8), represent the fundamental chemical reactions that occur during biomass gasification.

Char gasification:

$$C + H_2O \rightarrow CO + H_2 - 131.5\ \text{kJ/mol} \tag{4}$$

Water-gas shift reaction:

$$CO + H_2O \leftrightarrow CO_2 + H_2 + 141\ \text{kJ/mol} \tag{5}$$

Steam methane reforming:

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 - 206\ \text{kJ/mol} \tag{6}$$

Boudouard reaction:

$$C + CO_2 \rightarrow 2CO - 172\ \text{kJ/mol} \tag{7}$$

Methanation reaction:

$$C + 2H_2 \leftrightarrow CH_4 + 74.8\ \text{kJ/mol} \tag{8}$$

Biomass gasification can be carried out using various gasifying agents, such steam, oxygen, air, carbon dioxide, or their combination, depending on the intended application of the resulting syngas [11]. The syngas produced from biomass gasification consists mainly of H_2, CO, CO_2, CH_4, H_2O, and N_2, along with trace amounts of other compounds. It is also mixed with condensable components such as tar and unconverted carbon (char) [12]. Several challenges hinder the efficiency of biomass gasification, including the low energy density of biomass, its high moisture content, and its variable chemical composition. These factors contribute to inefficiencies in energy conversion and necessitate extensive pre-treatment processes, such as drying and grinding, which significantly increase cost and operational complexity. Moreover, supply chain constraints and land use limitations present obstacles to the large-scale adoption of biomass as a primary energy source.

In contrast, plastic waste management remains a significant global challenge due to its non-biodegradable nature. The rapid increase in plastic production, which reached 322 million tons worldwide in 2015 [13], has exacerbated environmental concerns. However, plastics possess a high calorific value, making them viable feedstock for energy recovery through processes such as gasification [14].

With its ability to process diverse feedstocks, gasification offers a promising solution for converting plastic waste into syngas, contributing to sustainable waste management and energy production [15].

One of the primary challenges in plastic gasification is the high tar content in syngas compared to biomass gasification, necessitating costly downstream cleaning processes. Additionally, polymer agglomeration affects gas composition and yield, reducing overall gasification efficiency [16]. A promising solution to address these issues is co-gasification, which involves blending of feedstocks, such as plastic waste with other feedstocks, such as biomass or coal. This approach enhances process efficiency, improves syngas quality, and minimizes environmental impacts by incorporating materials with higher energy content or more stable chemical properties [17]. Furthermore, co-gasification helps address supply and cost limitations associated with biomass use alone. The co-gasification of biomass and plastic waste offers several benefits, including higher H/C ratio of plastic can counteract the greater O_2 concentrations in biomass, resulting in increased H_2 generation and decreased char yield. Additionally, there are increases in the quantity and quality of gas with a better heating value than biomass mono-gasification [18]. Various gasifier types, such as fluidized bed, fixed bed, and entrained-flow gasifiers, have been explored in co-gasification studies to optimize performance and efficiency. Fluidized bed reactors are widely preferred for co-gasification due to their rapid reaction rates, efficient gas-solid interactions, low tar yields, and superior temperature control. These advantages make them particularly well-suited for optimizing syngas production in co-gasification processes [19]. Fig. 3 represents a schematic diagram of the co-gasification process highlighting the production of various valuable products.

Simulation studies play a critical role in the design of sustainable energy systems, particularly in biomass gasification. These studies help identify the best conditions for maximizing syngas production and improving process efficiency. Several models, including artificial neural networks, kinetic models, computational fluid dynamics models, and equilibrium models, are used for simulation [20]. Among these, equilibrium models are especially useful for simplifying complex systems into manageable frameworks that can predict system performance. These models handle reactions efficiently by allowing the system to reach chemical equilibrium quickly, although real gasifiers have reaction rates that dependent on time [21]. Equilibrium models are divided into stoichiometric and non-stoichiometric approaches. Various models have been developed to simulate biomass gasification and understand factors influencing gasification outcomes [22]. Numerous studies have examined the effects of various gasifying agents on the syngas composition, the hydrogen-carbon ratio, and the lower heating value (LHV) during the co-gasification of biomass and plastic waste. For example, Burra et al. [23], explored the use of steam as a gasifying agent in the co-gasification of biomass and plastic waste. They adjusted the biomass-to-plastic ratio in a semi-batch reactor at 1173 K to optimize syngas production and determine the optimal yields of H_2, CO and CO_2. Furthermore, Ajorloo et al. [24] developed a model using Aspen Plus in combination with Response Surface Methodology (RSM) to evaluate the effects of operational parameters during the co-gasification of pinewood and high density polyethylene (HDPE). Their findings indicate that the interaction between temperature and the steam-to-fuel ratio has the most significant influence on the results. An increase in temperature has a more pronounced impact on H_2 concentration when the steam-to-fuel ratio is 0.6 above this value, the high steam-to-fuel ratio can limit the effective conversion of feedstock, thus affecting the overall hydrogen yield [14]. Furthermore, increasing the steam-to-fuel ratio within the appropriate limits promotes higher H_2 production, particularly at lower operating temperatures. Tian et al. [7] developed an Aspen Plus model to simulate the co-gasification of rice husk and polyethylene under a steam atmosphere. Their results showed that increasing

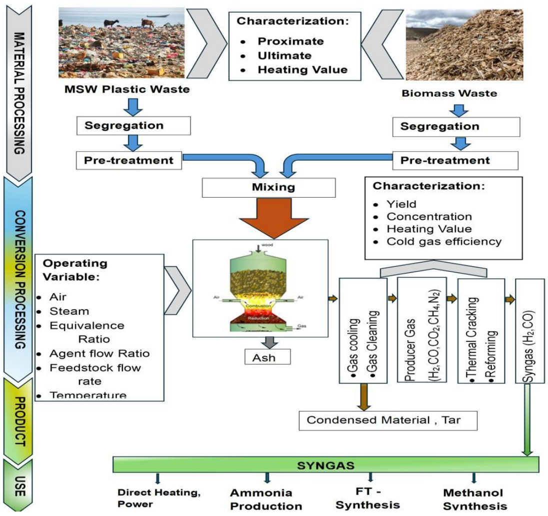

Fig. 3 Scheme of co-gasification to product application [19]

the proportion of plastic in the feedstock enhanced both the higher heating value of syngas and the hydrogen yield. Khumalo et al. [16] studied the co-gasification of sawdust and low-density polyethylene (LDPE) plastic waste, focusing on the parameters among different blend ratios (25%, 50% and 75%) and operating conditions such as the equivalence ratio (ER), which varied between 0.1 and the carbon -to-carbon dioxide (CO_2/C) ratio, which varied between 0-1.4 and how these affect syngas production. Using Aspen Plus, the study found that optimal syngas with high hydrogen content, a LHV of 9.2 MJ/Nm^3, and high H_2/CO ratios was produced at an ER below 0.4 and a CO_2/C ratio of 0.6. Singh et al. [15] developed a kinetic model in Aspen Plus to simulate the co-gasification of sawdust with two types of plastics, polyethylene and polypropylene, using steam as a gasifying agent. They varied the steam-to-fuel ratio (SFR) between 0.25-1.25. Their study found that at a temperature of 750 °C, the highest hydrogen concentrations were obtained, reaching 65.32% for polyethylene and 63.80% for polypropylene, with a plastic content of 30%. Kannan et al. [25] investigated the gasification of plastic waste using CO_2 and CO_2-steam blends as gasifying agents. When CO_2 was used alone, the resulting product gas was rich in CO, which led to a lower H_2/CO ratio. However, by increasing the steam ratio while keeping the CO_2/feed ratio constant, they observed a reduction in CO concentration and an increase in hydrogen concentration. Their simulation results demonstrated that CO_2 has potential as an effective gasifying agent.

Although several studies have explored the co-gasification of biomass and plastic waste using various gasifying agents, such as air, steam, and carbon dioxide, none have focused on the combination of pine sawdust and LDPE in the presence of pure oxygen. Literature shows that studies often use a range of gasifying agents, but did not investigate the specific interactions and effects when oxygen is employed, especially in the context of how the blend ratios of the feedstocks and the ERinfluence the process. Specifically, there are limited studies that examines the effect of using pine sawdust and low-density polyethylene as feedstocks with pure oxygen in the co-gasification process, particularly focusing on the synergistic interactions between these materials and the influence of oxygen on key outputs such as syngas composition, gas yield (GY), LHV and cold gas efficiency (CGE). By addressing this gap, this study aims to explore how these feedstocks, when co-gasified with oxygen, interact and how key parameters such as syngas composition, GY and CGE are affected. Understanding these interactions is crucial for improving the efficiency and sustainability of biomass and plastic waste gasification, providing a deeper understanding of how to optimize these processes for energy production and waste management.

2 Approach

2.1 Aspen Plus simulation assumptions

The flowsheet developed for the co-gasification of biomass and low-density polyethylene using Aspen Plus simulator is based on several assumptions to simplify the model. These assumptions are incorporated into the model using a non-stoichiometric approach [26], and the process is assumed to operate at a steady state. The products from the decomposition process are H_2, CO, CO_2, CH_4, H_2O and char. Other key assumptions include:

- The syngas produced comprises mainly H_2, CO, CO_2, CH_4, N_2, and H_2O.
- The gasifier is operated at atmospheric pressure.
- There is no pressure drop in the gasifier.
- Tar formation is considered negligible.
- Heat lost by the gasifier is considered negligible.

2.2 Model Development

In this study, an Aspen Plus simulation software (version 12) was used to simulate the co-gasification of. Biomass and plastic waste (low-density polyethylene) were used as feedstocks, and presented as different blends in the model, including 25% PE, 50% PE and 75% PE. Since the exact chemical formulas of these materials were not included in the Aspen Plus database, they were categorized as non-conventional components. The Peng-Robinson equation of state, with the Boston-Mathias alpha function was applied to estimate the thermodynamic properties of the conventional components in the co-gasification process. This method was chosen because it is effective in handling low operating pressures and high temperatures (>700 °C), which are typical in co-gasification processes [27]. To model non-conventional components like biomass and plastic waste, HCOALGEN and DCOALIGT property models were applied for enthalpy and density calculations, using proximate and ultimate analyses. The physical properties of biomass (determined using an elemental analyzer) and plastic waste were determined based on their proximate and ultimate analyses [28], as shown in Table 1. Particle size distribution for these non-conventional components was not considered in the simulation. The stream class "MIXCINC" was selected to account for both conventional and non-conventional solids in the simulation.

Table 1 Proximate and ultimate analysis of biomass and plastic waste

Source	Biomass (Pine sawdust)	Plastic waste (Low-Density Polyethylene)
Ultimate analysis (wt% dry basis)		
C	45.5	85.8
H	5.0	13.9
O	47.1	0
N	0.05	0.12
S	0	0.03
Ash	2.35	0.15
Proximate analysis (wt% dry basis)		
Fixed carbon	18.45	0
Volatile matter	79.20	99.85
Ash	2.35	0.15

The model incorporated two key input parameters: feedstocks (pine sawdust as biomass and low-density polyethylene (LDPE) as plastic waste and their respective blend ratios (25% PE, 50% PE and 75% PE) and ER. ERis defined as the ratio of the actual amount of oxygen supplied to the gasifier to the stoichiometric amount of oxygen required for complete combustion, as shown in Eq. (9) below:

$$\mathrm{ER} = \frac{\text{mass flow rate of oxygen supplied}}{\text{mass flow rate of stoichiometric oxygen}} \tag{9}$$

2.3 Performance parameters

The system performance is evaluated using key output indicators, including the LHV of syngas, the GY and the CGE [29]. The LHV of syngas represents the energy released during complete oxidation, excluding the energy needed to vaporize the water present in the combustion products. The formula for calculating the LHV of syngas is shown in Eq. (10) [24].

$$\mathrm{LHV}\left(\frac{\mathrm{MJ}}{\mathrm{Nm}^3}\right) = \frac{\left(10.8\times \mathrm{H}_2 + 12.6\times \mathrm{CO} + 35.8\times \mathrm{CH}_4\right)}{100}, \tag{10}$$

where H_2, CO, CH_4 represent the volumetric percentages of hydrogen, carbon monoxide, and methane, respectively. The constants 10.8, 12.6 and 35.8 are the LHVs of the respective gases in MJ/Nm^3.

CGE is an important indicator of thermal conversion efficiency, representing the ratio of chemical energy in the syngas (product gas) to the chemical energy in the feedstock (input fuel), typically expressed as a percentage. It is expressed using Eq. (11) [30].

$$\mathrm{CGE} = \left(\frac{\mathrm{LHV}_{\mathrm{syngas}} \times \text{ flow rate}_{\mathrm{syngas}}}{\mathrm{LHV}_{\mathrm{feedstock}} \times \text{ flow rate}_{\mathrm{feedstock}}}\right)\times 100 \tag{11}$$

GY is defined as the ratio of volumetric flow of syngas produced to the mass flowrate of the feedstock fed to the gasifier. It is expressed by Eq. (12) [30].

$$\mathrm{GY}\left(\frac{\mathrm{Nm}^3}{\mathrm{kg}_{\mathrm{fuel}}}\right) = \left(\frac{\text{volumetric flow rate}_{\mathrm{syngas}}\left(\frac{\mathrm{Nm}^3}{\mathrm{h}}\right)}{\text{mass flow rate}_{\mathrm{feedstock}}\left(\frac{\mathrm{kg}}{\mathrm{h}}\right)}\right) \tag{12}$$

2.4 Process and unit block description

Fig. 4 illustrates the process where feedstocks such as biomass, plastic waste and their respective blend ratios (25% PE, 50% PE and 75% PE) are fed into the RYield reactor (DECOMP) at a constant feed rate of 100 kg/h. In the DECOMP reactor, the feedstock undergoes thermal decomposition (pyrolysis) in the absence of oxygen at a specified temperature of 500 °C. The biomass and plastic waste are broken down into elemental constituents, such as C, H_2, O_2, H_2O and ash based on predefined yield distributions. A calculator block with FORTRAN subroutines is used to determine the yield based on the feedstock's ultimate analysis. The conventional components are introduced into the RGibbs reactor (GASIFIER) through the output stream (CONVE). The RGibbs reactor, anequilibrium reactor, determines the product composition by minimising Gibbs free energy. During the co-gasification of biomass and plastic waste, oxygen, used as a gasifying agent, reacts with the feedstock to produce syngas, consisting of the components such as CO, CO_2, CH_4 and H_2. The oxygen flowrate is adjusted using the input parameter, the ER, which is varied between 0.1 and 1. This parameter also helps regulate the temperature within the gasifier. Additionally, heat from the DECOMP unit is conveyed via the heat stream (Q-DECOMP), influencing the gasifier temperature. The products from the gasifier exit the RGibbs reactor through the outlet stream (PRODUCT) and enters acyclone (SEPARATE), which is set at 100% efficiency. Solid residues are separated from the sygas stream, with char and ash collected at the bottom of the separator through (SOLIDS) stream. Purified syngas exits at the top (GASES stream.)

Table 2 provides a description of the Aspen Plus unit blocks corresponding to the flowsheet (Fig. 4). It outlines the key components and processes involved in simulation.

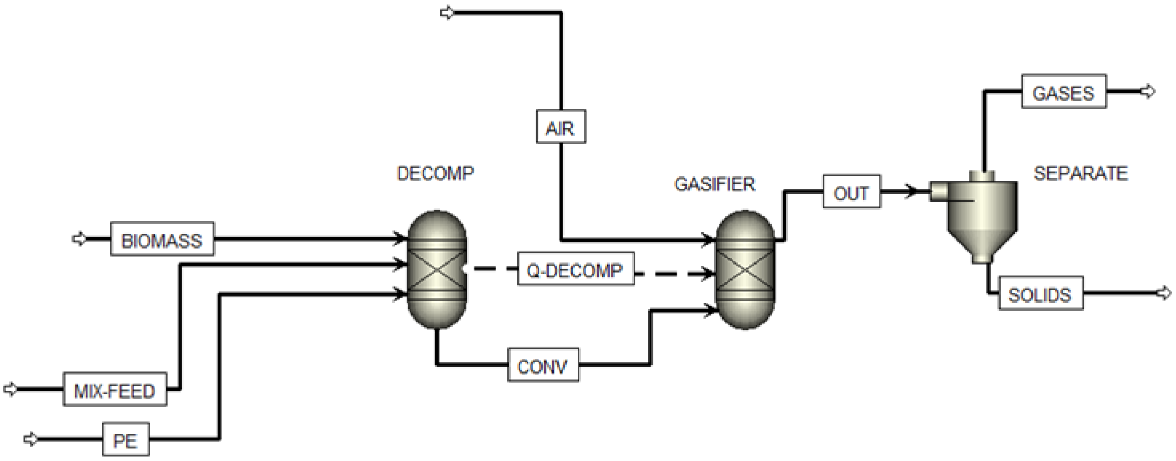

Fig. 4 Flow-sheet for the process simulation for the co-gasification of biomass and plastic waste

Table 2 Description of unit blocks utilized in the simulation

Unit block and ID	Description
RYield (DECOMP)	Models a reactor by specifying reaction yields of each component. This model is useful when reaction stoichiometry and kinetics are not known, and yield distribution data is available. (specified input is the temperature, which is set at 500 °C).
RGibbs (GASIFIER)	Models single-phase chemical equilibrium, or simultaneous phase and chemical equilibrium by minimizing Gibbs free energy, subject to atom balance constraints. The model is useful when temperature and pressure are known, and reaction stoichiometry is unknown (the specified input is ER, which ranges between 0.1-1).
Cyclone (GASIFIER)	The cyclone separates solid residues from gases. (specified parameter is a cyclone efficiency of 100%).

2.5 Model validation

To validate the simulation results, experimental data from a lab-scale co-gasification experiment using biomass (straw) and plastic waste (polyethylene) was used. Details of the experimental set-up can be found in the literature [31]. The input parameters for the experiment included an ER fixed 0.25 and a temperature of 1000 °C with air serving as a gasifying agent. The validation method used was the relative error method, which calculates the ratio between the absolute error (the difference between the modeled (Aspen Plus) value, (Xm), and experimental (Xe) values, over the experimental value (Eq. (13)). This method is useful in determining whether the model overestimates (positive error) or underestimates (negative error) the results [32]. The relative error between the model and experimental results was calculated and presented in Table 3 and Fig. 5. The results indicate that the syngas composition values from the Aspen Plus and the experiment are in good agreement, with relative errors within +/− 15%, which is considered acceptable according to Andres et al. [32]. The model seems to have underestimated composition of methane compared to those from other components. However, the values for methane are still within an acceptable range.

Table 3 Comparison of the model and experimental composition results for the co-gasification of biomass and plastic waste

Parameter	Experimental (Xe)	Model (Aspen Plus) (Xm)	Error (%)
H_2	13	12.76	−1.846
CO	13.6	13.81	1.471
CO_2	8.5	8.47	−0.353
CH_4	3.4	2.93	−13.82

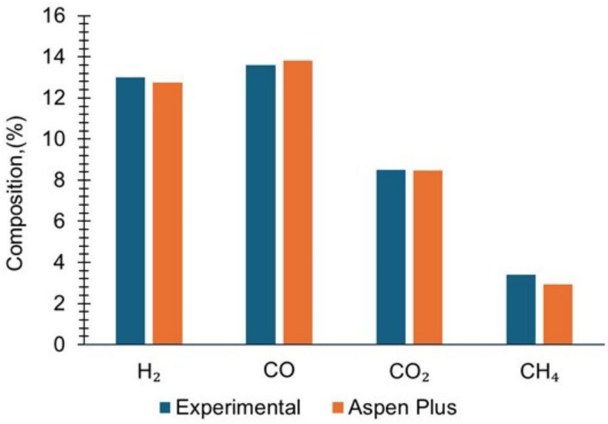

Fig. 5 Comparison of Aspen Plus values with experimental values using biomass and plastic waste data for model validation

$$\text{Error}(\%) = \frac{\text{model value} - \text{experimental value}}{\text{experimental value}} \times 100 \quad (13)$$

3 Results and discussion

3.1 Effect of oxygen as a gasifying agent on the H_2 composition of the product gas

Fig. 6 illustrates the effect of the ER on the hydrogen content in the syngas during the co-gasification of biomass and plastic waste using oxygen as the gasifying agent, across different feedstock blend ratios. The results show that as the ER increases from 0.1 to 1, the H_2 composition generally decreases for all feedstocks, except for 100% PE, where it initially rises, reaches a peak, and then declines as the ER continues to increase.

Higher H_2 concentrations are favored at lower ER values below 0.4, where reactions such as partial oxidation is favoured. At ER values above 0.4, complete oxidation reactions become more dominant, leading to the conversion of H_2 into H_2O. Additionally, Fig. 3 indicates that increasing the proportion of plastic waste in the feedstock enhances the H_2 composition in the syngas. This is attributed to the high H_2 content and volatile matter content in polyethylene, which contributes to greater H_2 production during co-gasification [17]

As a result, among the blended feedstocks, the highest H_2 composition of 56% at an ER of 0.1 was achieved with the blend ratio of 75% PE + 25% biomass. Other blends also exhibited high H_2 compositions at the same ER, with 25% PE + 75% biomass reaching 51.5% and 50% PE + 50% biomass achieving 54%. The high H_2 content is due to the increased plastic content in the feedstock, which has a higher hydrogen-to-carbon (H/C) ratio. This leads to the formation of more hydrogen (H) and hydroxyl ($^-$OH) radicals, enhancing the breakdown of aromatic compounds in the biomass [33].

3.2 Effect of oxygen as a gasifying agent on the CO compositions of the product gas

Fig. 7 shows how the ER and feedstock composition affect the CO content in syngas when using oxygen as the gasifying agent. The results indicate that a higher CO content is achieved at lower ERs below 0.4 because reactions like partial oxidation take place. However, when the ER exceeds 0.4, oxidation reactions become dominant, which reduces the CO content by converting it into CO_2 as the ER increases, the CO content gradually decreases, reaching a peak before declining further. This pattern is seen in all feedstocks except for 100% biomass, where CO continuously decreases as the ER rises. The drop in CO levels with higher ERs is mainly due to the increased oxygen supply, which encourages complete oxidation reactions. With more oxygen available, CO is more likely to convert into CO_2, leading to a lower CO yield and a higher CO_2 content in the syngas.[34]

Fig. 7 shows that as the percentage of plastic waste increases, the CO content in the syngas decreases. This happens because polyethylene has no oxygen and contains low fixed carbon. The highest CO content (56.4%) is observed at an ER of 0.1 when using pure biomass. Among the blended feedstocks, the highest CO content (54.2%) is achieved at an ER of 0.22 with a blend of 25% polyethylene and 75% biomass. This is followed by blends of 50% PE + 50% biomass and 75% PE + 25% biomass, both reaching 51.8% CO at an ER of 0.32. The high levels of H_2 and CO in these blends suggest that biomass and plastic waste interact beneficially during co-gasification.

3.3 Effect of using oxygen as a gasifying agent on the H_2/CO ratio of the syngas

Fig. 8 shows the effect of ER on the H_2/CO ratio during the co-gasification of biomass and plastic waste, when oxygen is used as the gasifying agent. The results indicate that as the ER increases, the H_2/CO ratio decreases. The highest H_2/CO ratios occur at low ER values (below 0.3) due

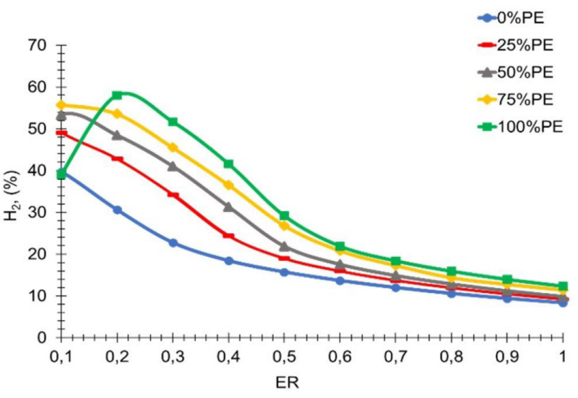

Fig. 6 Effect of the ER on H_2 composition in the product gas, when oxygen is used as gasifying agent

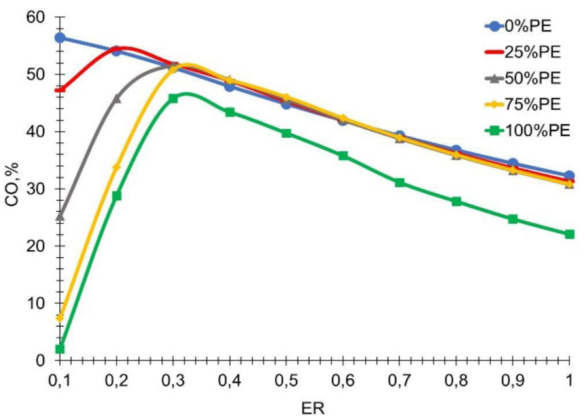

Fig. 7 Effect of the ER on CO composition in product gas, when oxygen is used as gasifying agent during the co-gasification of biomass and plastic waste

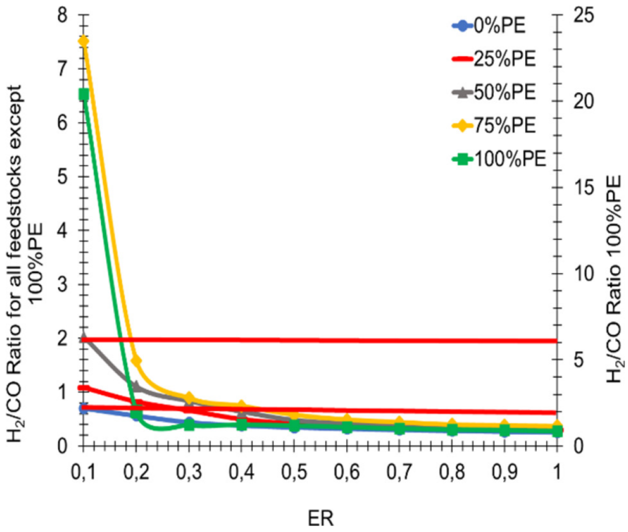

Fig. 8 Effect of the ER on the H_2/CO ratio of the syngas when oxygen is used as gasifying agent for the gasification at different blend ratios

to the presence of plastic waste in the feedstock, which is rich in hydrogen and boosts overall hydrogen production. Additionally, at low ER, the gasification process is less oxidizing, further favoring hydrogen formation [35].

Fig. 8 also reveals that increasing the amount of plastic waste in the feedstock leads to a higher H_2/CO ratio in the syngas. This happens because plastic waste has high volatile matter, low fixed carbon, and no oxygen. The ideal H_2/CO ratio of 2 was achieved with a blend of (50% PE + 50% biomass) at an ER of 0.1 and (75% PE + 25% biomass) at an ER of 0.2. Reaching this recommended ratio suggests that combining biomass and plastic waste improves syngas quality, demonstrating a beneficial interaction between the two feedstocks during co-gasification.

3.4 Effect of ER on the LHV of the syngas

Fig. 9 illustrates how the ER affects the LHV of syngas when oxygen is used as a gasifying agent during the co-gasification of biomass and plastic waste. The figure shows that for individual feedstocks, such as biomass and polyethylene, the LHV of syngas decreases as the ER increases. However, for blended feedstocks, like (25% PE + 75% biomass), (50% PE + 50% biomass) and (75% PE + 25% biomass), the LHV initially increases with rising ER, reaches a peak, and then starts to decline as ER continues to rise. The syngas has the highest energy content (LHV) when the ER is below 0.4 for all feedstocks.

This is because partial oxidation reaction are more active at low ER values. Adding more plastic waste to the feedstock increases the syngas energy content, as seen from the higher LHV of mixed feedstocks compared to using only biomass. However, Fig. 9 shows that mixing biomass and plastic waste does not create a synergistic effect that improves the LHV of the syngas. The highest LHV is obtained from polyethylene alone, not from the blended feedstocks. This suggests that when oxygen is used as the gasifying agent, there is no interaction between biomass and plastic waste that enhances syngas quality.

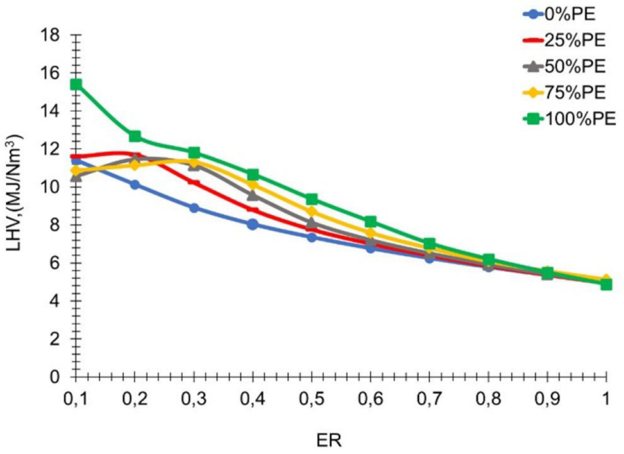

Fig. 9 Effect of the ER and feedstock compositions on the LHV of the syngas when oxygen is used as gasifying agent

3.5 Effect of ER on the GY

In Fig. 10, two blended feedstocks, (25% PE + 75% biomass) and (50% PE + 50% biomass), were used to study the effect of oxygen as a gasifying agent during the co-gasification on the GY. The results show that as the ER increases, the GY also increases in both blends. This happens because increasing the oxygen concentration as a gasifying agent enhances GY by raising the temperature in the gasifier, leading to more efficient conversion of feedstock into syngas [36].

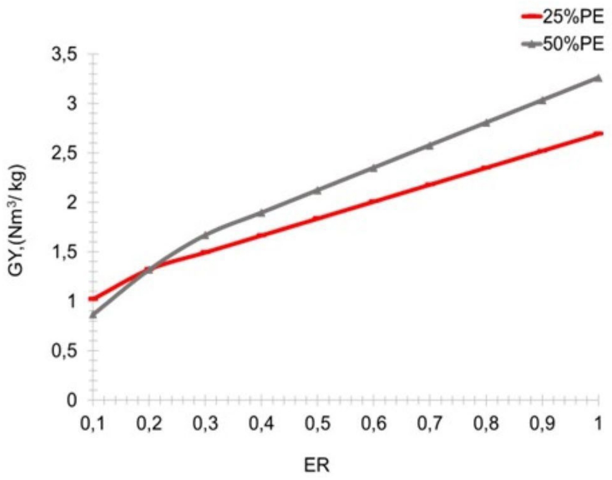

Fig. 10 Effect of the ER on GY when oxygen is used as gasifying agent for the co-gasification of biomass and plastic waste

As a result, the highest syngas yield of 3.2 Nm³/kg is achieved at an ER of 1 with a blend ratio of (50% PE + 50% biomass) blend. In comparison, a syngas yield of 2.6 Nm³/kg is obtained at the same an ER when using a (25% PE + 75% biomass) blend.

3.6 Effect of ER and feedstock composition on the CGE

In Fig. 11, as the ER increases, the CGE initially rises, reaching a peak before declining at higher ER values. The highest CGE occurs at low ER values below 0.5 due to the addition of plastic waste to the biomass feedstock increases the hydrogen content while reducing the oxygen content, leading to improved syngas production. Furthermore, the addition of plastic waste to the biomass feedstock increases the hydrogen content while reducing the oxygen content, leading to improved syngas production. As shown in Fig. 8, the highest CGE of 59% is achieved at an ER of 0.32 with a 50% PE + 50% biomass blend, while a maximum CGE of 58% is reached at an ER of 0.22 with a 25% PE + 75% biomass blend [14].

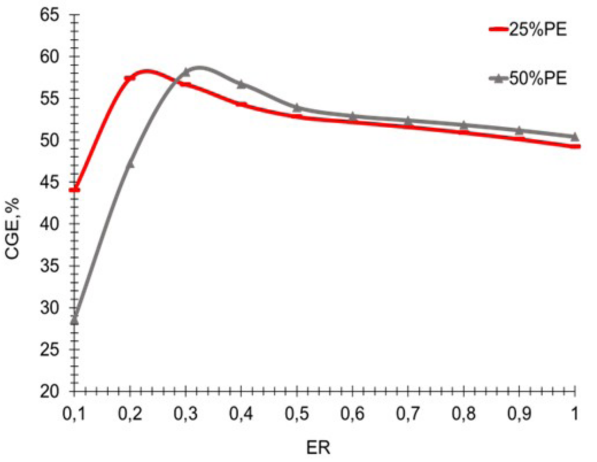

Fig. 11 Effect of the ER and feedstock compositions on CGE when oxygen is used as a gasifying agent for the co- gasification of biomass and plastic waste

This suggests that adding plastic waste improves both the syngas yield and CGE when oxygen is used as a gasifying agent. Figs. 10 and 11 confirm that plastic waste enhances both the GY and CGE. This is because plastics have a polymeric structure with high volatile matter, low fixed carbon, and low oxygen content, which promotes higher gas production and energy efficiency during co-gasification.

4 Conclusions

The results show that adding plastic waste to biomass in the presence of oxygen improves the production of H_2, CO, H_2/CO ratio, GY, and CGE at low ER below 0.3. At an ER of 0.1, the H_2 composition increased with higher plastic waste content, reaching 51.5% for (25% PE + 75% biomass), 54.0% for (50% PE + 50% biomass), and 56.0% for (75% PE + 25% biomass). The highest GY of 3.2 Nm³/kg was achieved at (50% PE + 50% biomass) at an ER of 1, while the highest CGE of 59% occurred at an ER of 0.32 with the same blend. These improvements are attributed to the influence of partial oxidation reaction at low ER and the polymeric nature of plastic waste, consisting of high hydrogen content and low oxygen content, which enhances the synergistic interaction between biomass and plastic during co-gasification. However, the results also indicate that this synergy negatively impacts the LHV of the syngas. Furthermore, an increase in ER raises the GY, while other parameters are optimized at low ER values.

Acknowledgements

The project presented in this article is supported by the University of South Africa (UNISA), Department of Chemical and Materials Engineering.

References

[1] Fu, W., Zhang, Y., Cui, L., Liu, H., Masqsood, T. "Experimental microwave-assisted air gasification of biomass in fluidized bed reactor", Bioresource Technology, 369, 128378, 2023. https://doi.org/10.1016/j.biortech.2022.128378

[2] Serrano-Ruiz, J. C. "Biomass: A Renewable Source of Fuels, Chemicals and Carbon Materials", Molecules, 25(21), 5217, 2020. https://doi.org/10.3390/molecules25215217

[3] Tursi, A., Olivito, F. "Biomass conversion: general information, chemistry, and processes", In: Advances in Bioenergy and Microfluidic Applications, Elsevier, 2021, pp. 3–39. ISBN: 978-0-12-821601-9 https://doi.org/10.1016/B978-0-12-821601-9.00001-7

[4] Cao, Y., Bai, Y., Du, J. "Parametric study on biomass gasification by using air, oxygen-enriched air, air/steam and oxygen-enriched air/steam agents: An ASPEN plus modeling", International Journal of Hydrogen Energy, 73, pp. 265–273, 2024. https://doi.org/10.1016/j.ijhydene.2024.06.037

[5] Yahaya, A. Z., Somalu, M. R., Muchtar, A., Sulaiman, S. A., Daud, W. R. W. "Effect of particle size and temperature on gasification performance of coconut and palm kernel shells in sowndraft fixed-bed reactor", Energy, 173, pp. 931–940, 2019. https://doi.org/10.1016/j.energy.2019.03.138

[6] Hussain, M., Ali, O., Raza, N., Zabiri, H., Ahmed, A., Ali, I. "Recent advances in dynamic modeling and control studies of biomass gasification for production of hydrogen rich syngas", RSC Advances, 13(34), pp. 23796–23811, 2023. https://doi.org/10.1039/D3RA01219K

[7] Tian, Y., Luo, Z., He, D., Yang, D., Liang, S., Liu, W., Yuan, L. "Co-gasification of biomass and polyethylene: A simulation study by considering tar formation", Biomass Conversion and Biorefinery, 14(3), pp. 4081–4089, 2024. https://doi.org/10.1007/s13399-022-02848-9

[8] Okati, A., Khani, M. R., Shokri, B., Monteiro, E., Rouboa, A. "On the operating parameters for hydrogen-rich syngas production in a plasma co-gasification process of municipal solid wastes and polyethylene using a constrained model in Aspen plus", Journal of the Energy Institute, 107, 101173, 2023. https://doi.org/10.1016/j.joei.2023.101173

[9] Sansaniwal, S. K., Pal, K., Rosen, M. A., Tyagi, S. K. "Recent advances in the development of biomass gasification technology: A comprensive review", Renewable and Sustainable Energy Reviews, 72, pp. 363–384, 2017. https://doi.org/10.1016/j.rser.2017.01.038

[10] Roh, K., Lee, J. H. "Control Structure Selection for the Elevated-pressure Air Separation Unit in an IGCC Power Plant Self-optimizing Control Structure for Economical Operation", Industrial & Engineering Chemistry Research, 53(18), pp. 7479–7488, 2014. https://doi.org/10.1021/ie402909j

[11] Rubinsin, N. J., Karim, N. A., Timmiati, S. N., Lim, K. L., Isahak, W. N. R. W. Pudukudy, M. "An overview of the enhanced biomass gasification for hydrogen production", International Journal of Hydrogen Energy, 49, pp. 1139–1164, 2024. https://doi.org/10.1016/j.ijhydene.2023.09.043

[12] Shen, Y. "Biomass pretreatment for steam gasification toward H_2-rich syngas production - An overview", International Journal of Hydrogen Energy, 66, pp. 90–102, 2024. https://doi.org/10.1016/j.ijhydene.2024.04.096

[13] Ibrahim, A., Veremieiev, S., Gaskell, P. H. "An Advanced, Comprehensive Thermochemical Equilibrium Model of a Downdraft Biomass Gasifier", Renewable Energy, 194, pp. 912–925, 2022. https://doi.org/10.1016/j.renene.2022.05.069

[14] Khumalo, N. L., Patel, B. "A parametric analysis of the Co-gasification of biomass and plastic waste using Aspen Plus", Computer Aided Chemical Engineering, 52, pp. 1421–1426, 2023. https://doi.org/10.1016/B978-0-443-15274-0.50226-2

[15] Singh, M., Salaudeen, S. A., Gilroyed, B. H., Dutta, A. "Simulation of biomass-plastic co-gasification in a fluidized bed reactor using Aspen plus", Fuel, 319, 123708, 2022. https://doi.org/10.1016/j.fuel.2022.123708

[16] Khumalo, N. L., Patel, B. "Modelling of the Co-gasification of Waste Plastic and Biomass using Oxygen – CO_2 Mixtures", Computer Aided Chemical Engineering, 53, pp. 361–366, 2024. https://doi.org/10.1016/B978-0-443-28824-1.50061-2

[17] Erdem, K., Han, D. G., Midilli, A. "A Parametric Study on Hydrogen Production by Fluidized Bed Co-gasification of Biomass and Waste Plastics", International Journal of Hydrogen Energy, 52, pp. 1434–1444, 2024. https://doi.org/10.1016/j.ijhydene.2023.10.115

[18] Halba, A., Thengane, S. K., Arora, P. "A Critical Outlook on Lignocellulosic Biomass and Plastic Co-gasification: A Mini – Review", Energy Fuels, 37, pp. 19–35, 2023. https://doi.org/10.1021/acs.energyfuels.2c02907

[19] Raj, R., Singh, D. K., Tirkey, J. V. "Co-gasification of plastic waste blended with coal and biomass: a comprehensive review", Environmental Technology Reviews, 12(1), pp. 614–642, 2023. https://doi.org/10.1080/21622515.2023.2283095

[20] Speight, J. G. "Synthetic Fuels Handbook: Properties, Process, and Performance", McGraw-Hill Education, 2020. ISBN: 9781260128963

[21] Kuswah, A., Reina, T. R., Short, M. "Modelling approaches for biomass gasifiers: A comprehensive overview", Science of the Total Environment, 834, 155243, 2022. https://doi.org/10.1016/j.scitotenv.2022.155243

[22] Zogala, A. "Critical of Underground Coal Gasification Models, Part 1: Equilibrium Models – Literacy Studies", Journal of Sustainable Mining, 13(1), pp. 22–28, 2014. https://doi.org/10.7424/jsm140105

[23] Burra, K. G., Gupta, A. K. "Synergistic effects in steam gasification of combined biomass and plastic waste mixtures", Applied Energy, 211, pp. 230–236, 2018. https://doi.org/10.1016/j.apenergy.2017.10.130

[24] Arjorloo, M., Ghodrat, M., Scott, J., Strezov, V. "Modelling and statistical analysis of plastic biomass mixture co-gasification", Energy, 256, 124638, 2022. https://doi.org/10.1016/j.energy.2022.124638

[25] Kannan, P., Lakshmanan, G., Al Shoaibi, A., Shrinivasakannan, C. "Equilibrium model analysis of waste plastic gasification using CO_2 and steam", Waste Management and Research, 35(12), pp. 1247–1253, 2017. https://doi.org/10.1177/0734242X17736946

[26] Donolo, G., Simon, G. D., Fermeglia, M. "Steady state simulation of energy production from biomass by molten carbonate fuel cells", Journal of Power Sources, 158(2), pp. 1282–1289, 2006. https://doi.org/10.1016/j.jpowsour.2005.10.045

[27] Ramzan, N., Ashraf, A., Navad, S., Malik, A. "Simulation of hybrid biomass gasification using Aspen plus: A comparison performance analysis is for food, municipal solid and poultry waste", Biomass and Bioenergy, 35(9), pp. 3962–3969, 2011. https://doi.org/10.1016/j.biombioe.2011.06.005

[28] Al Amoodi, N., Kannan, P., Al Shoaibi, A. Shrinivasakannan, C. "Aspen Plus Simulation of Polyethylene Gasification under Equilibrium Conditions", Chemical Engineering Communication, 200(7), pp. 7–9, 2013. https://doi.org/10.1080/00986445.2012.715108

[29] Inayat, M., Sulaiman, S. A., Kumia, J. C., Shahbaz, M. "Effect of Various Blended Fuels on Syngas Quality and Performance in Catalytic Co-gasification: A Review", Renewable and Sustainable Energy Reviews, 105, pp. 252–267, 2019. https://doi.org/10.1016/j.rser.2019.01.059

[30] Thomson, R., Kwong, P., Ahmado, E., Nigam, K. D. P. "Clean Syngas from Small Commercial Biomass Gasifiers and Review of Gasifier Development, Recent Advances and Performance Evalution", International Journal of Hydrogen Energy, 45(41), pp. 21087–21111, 2020. https://doi.org/10.1016/j.ijhydene.2020.05.160

[31] Yu, H., Yang, X., Jiang, L., Chen, D. "Experimental Study on Co-gasification Characteristics of Biomass and Plastic Wastes", BioResources, 9(3), pp. 5616–5626, 2014. https://doi.org/10.15376/biores.9.3.5615-5626

[32] De Andres, J. M., Vedrenne, M., Biambilla, M., Rodriguez, E. "Modelling and model performance evaluation of sewage sludge gasification in fluidized bed gasifiers using Aspen Plus", Journal of the Air and Waste Management Association, 69(1), pp. 23–33, 2019. https://doi.org/10.1080/10962247.2018.1500404

[33] Yek, P. N. Y., Chan, Y. H., Foong, S. Y., Mahari, W. A. W., Chen, X., …, Lam, S. S. "Co-processing plastics waste and biomass by pyrolysis-gasification: A review", Environmental Chemistry Letters, 22(1), pp. 171–188, 2024.
https://doi.org/10.1007/s10311-023-01654-7

[34] Li, S., Che, D., Yang, W., Wang, H. "The effect of ER on biomass gasification in a fixed bed using ASPEN PLUS simulation", In: World Automation Congress 2012, Puerto Vallarta, Mexico, 2012, pp. 1–4. ISBN: 978-1-889334-47-9 [online] Available at: https://ieeexplore.ieee.org/document/6321326 [Accessed: 01 December 2024]

[35] Fekhar, B., Al-Asadi, M. A. S., Khirennas, M. "Renewable hydrogen energy from polymeric waste: an Aspen Plus mode of date palm seeds and mixed synthetic materials co-gasification", Studies in Engineering and Exact Sciences, 5(3), e12400, 2024.
https://doi.org/10.54021/seesv5n3-020

[36] Yuan, H., Lu, T., Zhao, D., Wang, Y., Kobayashi, N. "Influence of Oxygen Concentration and Equivalence Ratio on MSW Oxygen -Enriched Gasification Syngas Composition", In: Dincer, I., Colpan, C., Kzilkan, O., Ezan, M. (eds.) Progress in Clean Energy, Volume 2, Springer Cham, 2015, pp. 165–176. ISBN: 978-3-319-17031-2
https://doi.org/10.1007/978-3-319-17031-2_13