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Modelling and Simulation of Co-Gasification of *Chlorella Vulgaris* and High-density Polyethylene Using Aspen Plus

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Abstract: *A technical innovation that holds promise for producing renewable fuel and decreasing waste disposal is the production of syngas from the co-gasification of waste materials and biomass. In this present study, a new simulation model for co-gasifying high-density polyethylene (HDPE) and microalgae using Aspen plus V10 was built. Several operating parameters, including operating temperature, air equivalence ratio (ER), biomass blending ratio, steam-to-biomass ratio (S/B), and air/steam ratio, were investigated for their influence on the yield and composition of H_2, CO, CO_2, and CH_4. Results indicated that these operating parameters had significant impacts on the gaseous products. High gasifier temperatures (1000°C) for the co-gasification process favored the formation of H_2 and CO and increased their yields. Also, the yield of H_2 significantly decreased when the value of the equivalence ratio was increased. According to simulation results, increasing the steam-to-biomass ratio favored the synthesis of H_2 and CO up to a point. In addition, waste plastic (HDPE) in the feedstock should be kept at a minimum to favor the production of hydrogen-rich gas. The findings show that the model results agree with previous experimental studies. This research study has proven the air-steam co-gasification of microalgae and HDPE as a suitable process for the production of syngas rich in hydrogen.*

Keywords: *Aspen Plus, Co-gasification, Biomass, Plastics, Syngas.*

1. INTRODUCTION

The unprecedented rise in economic and population growth has increased global energy demand. Fossil fuel depletion, in addition to the associated environmental pollution from fossil fuel combustion, which causes global warming and climate change, has prompted the investigation and development of sustainable energy systems [1, 2]. Biomass is considered a sustainable, renewable, carbon-neutral, environmentally friendly, and promising alternative source of fossil fuel energy due to its potential to contribute to the decarbonization of global energy systems (virtually no carbon footprint), whilst providing syngas and electricity [3]. It can be obtained from a wide range of sources, such as municipal solid waste, sewage, crops, and animal residue [4]. Several thermochemical processes such as gasification [5-7], pyrolysis [8], incineration [9], and combustion [10] offer the opportunity for converting biomass to energy, which is termed "waste-to-energy". Among these technologies, gasification is considered a feasible option for utilizing biomass to produce hydrogen-rich gases, which are considered clean energy owing to their low pollutant emissions like NO_x and SO_x [11].

Gasification can be defined as a thermal conversion process for converting biomass into gaseous products in (H_2, CO, CO_2, CH_4), and other compounds (tar, char, and ash) in the presence of gasifying agents at high temperatures ranging (700 - 1200^{o}C) [12, 13]. Researchers have proposed the co-gasification process for improving the quantity and quality of syngas [14]. Co-gasification using low carbon fuel has resulted in excellent outcomes in regards to the production of hydrogen-rich gas [15]. Data obtained from the US Environmental Protection Agency (EPA) and the American Chemistry Council (ACC) report that in 2017, the United States produced around 35.4 million tons of plastic waste. The amount of plastic waste recycled out of this total was roughly 3 million tons, implying that bulk of the plastic waste is disposed of in landfills or incinerators. Plastics that are commonly used include high-density polyethylene (HDPE), polypropylene (PP), and polystyrene (PS) [16, 17]. HDPE is the world's largest commodity of plastic waste, with alkane as its main product [18].

The gasification of plastics is an attractive technology to curb the environmental problems of plastic pollution and improve its utilization efficiency. However, due to their molten formation and high tar content, the gasification of plastics is still in its early stages and has yet to be deployed on an industrial scale [19]. As research advances, blending of plastic waste with biomasses has become a more appealing alternative for producing high-quality syngas with low tar content while avoiding the challenges associated with gasification of plastics, such as contamination accumulation and feeding problems [20]. Chai et al. [16] reported that plastic content in gasification feedstock would be beneficial in increasing H_2 yield. This is due to the high hydrogen/carbon ratio of plastic that provides more hydrogen radicals which increases the formation of hydrogen as a gaseous product.

Researchers have reported the co-gasification of plastics with biomasses as a favorable technique to degrade microplastics. Li et al. [19] studied the synergistic benefits of co-gasifying HDPE and pine wood which produced maximum synergistic impact with a 69 percent energy output. Pinto et al. [21] reported that the presence of waste plastic in the biomass/plastic co-gasification process was favorable for the release of H_2 and the decrease in CO concentration. Emad and Vahid [15] predicted the potential of co-gasifying asphaltene and plastics for the production of syngas using Aspen plus. They found out that the blend of plastics and asphaltene affected the syngas and energy yield. They also reported increased gas yields from 45.12 % to 92.08% with increasing equivalence ratio, while there was a decrease in the tar yield from 12.24% to 0.14%. Fan et al. [22] investigated the co-gasification of eucalyptus wood and risk straw with polyethylene. Results indicated that the addition of polyethylene was useful for decomposing the biomass. Xu et al. [23] investigated the co-gasification of biomass and polyethylene wastes in a bench-scale fixed bed reactor. The results displayed the positive outcome of co-feeding the biomass with polyethylene on the gas and tar yields. So far, these findings indicate that co-gasification of biomass and plastic is a promising technology for improving syngas quality, overcoming plastic disposal and processing issues, and contributing to plastic pollution reduction.

Researches on algae gasification are rather limited. Microalgae have a high heating value and a quick growth rate, making them potential feedstock for biofuels. It is feasible to grow in sewage, avoiding the expense of using clean water and fertilizer, makes the idea of generating energy from wastewater treatment facilities attractive. Onwudili et al. [24] reported the key findings from the catalytic hydrothermal gasification of different types of algae for the formation of hydrogen-rich gases. Mustapha et al. [25] studied the hydrothermal gasification of *Scenedesmus obliquus* (microalgae) for producing hydrogen-rich syngas. Atikah and Harun [26] utilized Aspen Plus for simulating the gasification of *chlorella vulgaris* to assess the influence of the operating parameters on syngas production and also optimize the gasification process for improved production of syngas.

Previous studies on the co-gasification of biomass (algae) and plastic for the production of syngas are currently limited and insufficient. Furthermore, experimental studies on the co-gasification of biomass and syngas are time-consuming and costly [27]. Thermodynamic modelling is faster and obviously cheaper than conducting experiments for studying the biomass/plastic co-gasification process. Therefore, the application of a suitable model for investigating optimal operating conditions helps to conserve resources and time [28-30]. In a bid to consolidate research on the co-gasification of biomass and plastic waste, this paper aims to improve the quality and yield of gaseous products from the co-gasification of microalgae (*Chlorella vulgaris*) and high-density polyethylene (HDPE) using the process simulator, Aspen Plus. The objective of this research study is to develop a thermodynamic model for the co-gasification process using Aspen Plus, observe the effect of the process parameters such as gasifier temperature, mixed-biomass ratio, steam-to-biomass ratio, gasifying agents, and air equivalence ratio (ER) on the gaseous products, and validate the model results with experimental data. The model will serve as a guide for improving the co-gasification process of biomass and waste plastic for the efficient production of syngas.

2. MATERIALS AND METHODS

2.1 Feedstock Characterization

Characteristics of microalgae (*Chlorella vulgaris*) and plastic waste (HDPE) used for this research study are shown in Table 1. The data used include the proximate and ultimate analysis values reported by Raheem et al. [31] and Yao et al. [7] for microalgae and plastic waste respectively.

2.2 Property Package Selection

IDEAL property method is preferred and selected for the simulation because it is the most suitable inbuilt method for the involved processes which include conventional components at high temperature ranges. The material feeds (Microalgae & Plastic) were specified as non-conventional (NC) solids by defining their standard enthalpy of formation and chemical composition. The density and enthalpy of the NC components are calculated with the use of DCOALIGT and HCOALGEN models. This is because of the unavailable characterization data of the NC components. The MCINCPSD stream class was selected due to the conventional and non-conventional streams present in the process. The gaseous products were defined using the MIXED sub stream and the solid products using the CISOLID sub stream.

2.3 Model Assumptions

The model was developed with the following assumptions:

i. The gasifier operates at a steady state with no heat loss.
ii. The gasifier operates at atmospheric pressure.

iii. There is uniform temperature and no pressure drop in the gasifier.
iv. The particles are all even-sized and spherical.
v. Any ash produced during the reactions in the gasifier, stays as a layer on the particles.
vi. The solid and gaseous phases are instantaneously and perfectly combined.
vii. The solid product 'Char' is made up of black carbon and ash.
viii. Volatile products include H_2, CO, CO_2, and CH_4.
ix. There is no formation of oxides of nitrogen and sulfur

Table 1: Ultimate and proximate analysis of the feedstock

Microalgae *(Chlorella vulgaris)*		**Plastic Waste (HDPE)**	
Proximate Analysis	**Composition (wt %)**	**Proximate analysis**	**Composition (wt %)**
Moisture content	6.3	Moisture content	0.25
Volatile matter	83.5	Volatile matter	94.77
Ash	6.1	Ash	4.98
Fixed carbon	10.4	Fixed carbon	-
Ultimate Analysis	**Composition (wt %)**	**Ultimate analysis**	**Composition (wt %)**
C	50.4	C	78.18
H	6.0	H	12.84
N	14.8	N	0.06
S	6.1	S	0.08
O	22.8	O	3.61

2.4 Model Description

The biomass gasification process for syngas production involves four main operations: biomass drying; biomass decomposition; gasification; and separation units [32]. The description of each unit operation is summarized in block units and shown in Table 2. A list of the components used in the Aspen Plus model is recorded and shown in Table 3.

Table 2: Unit Operations in the model

Process	**Block**	**Model ID**	**Process Description**	**Input Parameters**
Drying	RStoic	DRY-REAC	Removing moisture content from the algae biomass.	Pressure and heat duty are set to 1 bar and 0 Gcal/h respectively. Reaction: biomass→0.0555084H_2O.
Separation	Flash 2	SEP-01	Separating dried biomass (algae) from moisture content.	Pressure and heat duty are set to 1 bar and 0 Gcal/h respectively.
Decomposition	RYield	DECOMP1	Converting algae biomass contents to conventional components.	Temperature and Pressure are set to 500 °C and 1 bar respectively. C, S, ash, H_2, N_2, O_2, and H_2O are the possible products.
Heating	Heater	HEATER1	Heating the waste plastic before feeding the decomposer	Temperature and Pressure are set at 500 °C and 1 bar respectively.
Decomposition	RGibbs	DECOMP2	Converting plastic biomass contents to conventional components.	Temperature and Pressure are set to 650 °C and 1 bar respectively. CO, H_2, H_2O, CO_2, and CH_4 are the possible products.
Heating	Heater	HEATER2	Converting water to steam	Temperature 500 °C; pressure 1 bar.
Gasification	RGibbs	GASIFIER	Simulation of solid-gas reactions.	Pressure and Temperature are set to 1 bar and 800 °C respectively. H_2, N_2, CO, CO_2, C, S, H_2O, and CH_4 are the

Process	Block	Model ID	Process Description	Input Parameters
				possible products.
Separation	SSplit	SEP-02	Separating products syngas from char.	For the syngas stream, the MIXED sub-stream was set to 1. For the char stream, the CIPSD and NCPSD sub-stream were also set to 1

Table 3: Components used in the Aspen Plus model

Aspen Plus ID	Component Type	Component Name
Algae	Non-conventional	-
Plastic	Non-conventional	-
C	Solid	Carbon-graphite
CH_4	Conventional	Methane
H_2O	Conventional	Water
CO_2	Conventional	Carbon dioxide
O_2	Conventional	Oxygen
H_2	Conventional	Hydrogen
N_2	Conventional	Nitrogen
S	Conventional	Sulfur
Ash	Non-conventional	-
CO	Conventional	Carbon monoxide

The non-stoichiometric equilibrium method can be employed for the modelling and simulation of gasification processes that involve solid, liquid, and gas phases. The model calculates the gasification products and chemical equilibrium is determined by the minimization of Gibbs free energy [32]. According to past studies, this approach produces outcomes that are similar to their experimental counterparts using downdraft gasifiers [33].

For this study, 300 kg/hr was set as the biomass flow rate for both biomasses, and an (RYIELD) isothermal yield reactor was used to decompose the biomass feedstock (algae) into its constituent components based on the proximate and ultimate analyses. The inputs (steam, air, and mixed-biomass feedstock) were individually fed into the gasifier. The syngas produced from the gasifier was passed through a cyclone to separate the syngas from the solid product (char). By minimizing Gibbs free energy, Gibb's reactor simulates both oxidation and reduction reactions. Gasification involves several sets of chemical reactions, which are summarized in Equations 1 to 9.

Partial oxidation	$C + 0.5O_2 \leftrightarrow CO$	$\Delta H_{298} = -111$ MJ/kmol	(1)
CO combustion	$CO + 0.5O_2 \leftrightarrow CO_2$	$\Delta H_{298} = -284$ MJ/kmol	(2)
Water-Gas reaction	$C + H_2O \leftrightarrow CO + H_2$	$\Delta H_{298} = +131$ MJ/kmol	(3)
Water-Gas shift reaction	$CO + H_2O \leftrightarrow CO_2 + H_2$	$\Delta H_{298} = 42$ MJ/kmol	(4)
Methanation reaction	$C + 2H_2 \leftrightarrow CH_4$	$\Delta H_{298} = -74$ MJ/kmol	(5)
Steam-Methane reforming	$CH_4 + H_2O \leftrightarrow CO + 3H_2$	$\Delta H_{298} = +206$ MJ/kmol	(6)
CO_2 reforming	$CH_4 + CO_2 \leftrightarrow 2CO + 2H_2$	$\Delta H_{298} = +247$ MJ/kmol	(7)
Boudouard reaction	$C + CO_2 \leftrightarrow 2CO$	$\Delta H_{298} = +172$ MJ/kmol	(8)
Hydrogen combustion	$H_2 + 0.5O_2 \leftrightarrow H_2O$	$\Delta H_{298} = -484$ MJ/kmol	(9)

The flowchart of the simulated process is shown in Figure 1.

The actual yield of the algae decomposition block was calculated using a calculator block. The decomposition yield for H_2O, C, S, N_2, O_2, H_2, and ash were set to 0.2, 0.2, 0.1, 0.1, 0.1, 0.2, and 0.1mol, respectively. The 'COMBUST' calculator block was arranged to run before the biomass decomposition (DECOMP1) unit using a FORTRAN statement where FACT represented the factor utilized for the conversion of the ultimate analysis into a wet basis. The FOTRAN statement used in the calculator block is shown below:

FACT is the factor to convert the ultimate analysis to a wet basis.
FACT = (100 - WATER) / 100
H_2O = WATER / 100
ASH = ULT (1) / 100 * FACT
CARB = ULT (2) / 100 * FACT
H_2 = ULT (3) / 100 * FACT
N_2 = ULT (4) / 100 * FACT

SULF = ULT (6) / 100 * FACT
O_2 = ULT (7) / 100 * FACT

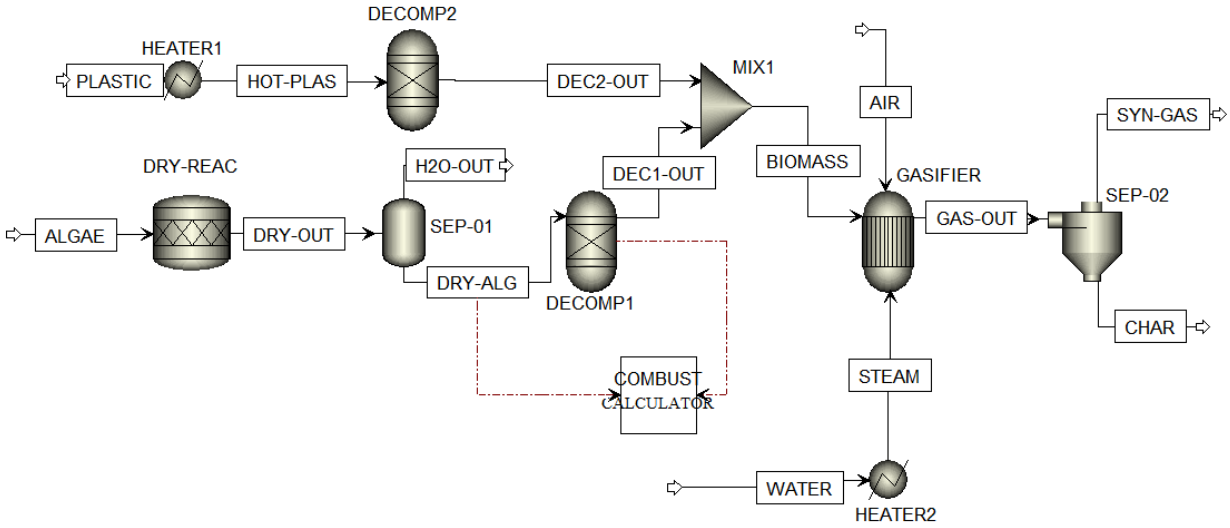

Figure 1: Flowchart of the simulated co-gasification process

2.5 Sensitivity Analysis

There is a need to study the system in terms of material inputs and output. To study the effect of input parameters on the co-gasification system, a sensitivity analysis tool was utilized. The gasifier has three inputs: steam, biomass, and air, all of which have an impact on system performance and syngas composition. At the GASIFIER block (Figure 1), analyses of temperature, steam-to-biomass ratio (S/B), air/steam ratio, air equivalence ratio (ER), and mixed-biomass ratio (A/P) were performed. The effect of each operating parameter on the gaseous product/syngas yield and mole composition was studied.

3. RESULTS AND DISCUSSION

3.1 Effect of Gasification Temperature

Temperature is very important during gasification as it has a significant influence on the syngas produced [34]. A parametric study was conducted to observe the influence of temperature on gaseous products (H_2, CO, CO_2, and CH_4). Temperature was varied (600 to 1000°C) while the other operating parameters were kept constant. The flow rate of the gasifying agents (air and steam) was fixed at 100 kg/hr, and both biomasses were fed at a rate of 300 kg/hr.

The mole composition and yield of the syngas generated by the co-gasification process as the temperature is altered, are shown in Figures 2 and 3 respectively. It was observed that the gasifier temperature is directly proportional to the mole fraction of H_2 and CO which increased. The mole fraction of H_2 increased from 0.37 at 600°C to 0.49 at 1000°C. The increase in the composition of H_2 and CO in the syngas are attributed to the reaction pathways in Equations 3, 6, 7, and 8 (Water-Gas, Steam-Methane reforming, CO_2 reforming, and Boudouard reactions). These reactions are all endothermic in nature and favor the yield of H_2 and CO at higher temperatures. From Figure 3, the yield of CH_4 and CO_2 was higher at lower temperatures. The methanation reaction (Equation 4), due to its exothermic nature, favors the production of CH_4 at lower temperatures. Also, the Steam-Methane and CO_2 reforming reaction (Equation 6 and 7) lead to a reduction in the yield of CH_4 and CO_2 because they are consumed as reactants [35]. These findings are consistent with a previous study by Raheem et al. [36], which also concluded that lower temperatures favoured the yield of CH_4 and higher temperatures favored the yield of H_2.

3.2 Effect of Air Equivalence Ratio (ER)

Air equivalence ratio (ER), which is determined by the volume of airflow into the gasifier, is another important parameter influencing the gaseous products. An investigation on the influence of the Air ER on the gaseous products is conducted by increasing the air flow rate into the gasifier. This is done to achieve an air ER ranging from 0.02 to 0.33. For the purpose of this study, the temperature is kept constant at 800°C, the biomass feed flow rate is maintained, and the gasification system receives steam at a constant rate of 100 kg/hr.

Figures 4 and 5 shows the mole compositions and yield of H_2, CO, CO_2, and CH_4 from the co-gasification process at various air ER. From Figure 4, as the ER increases, the mole composition of H_2 decreases from 0.54 to 0.47. In Figure 5, it is observed that there is a higher yield of CO and CO_2 as the air ER increases. This pattern is due to a greater conversion of the fuel's carbon content due to increased oxygen levels in the gasifier (Equation 1 and 2). Increase in oxygen content favors exothermic reactions like the combustion and oxidation reactions, which yield more CO and CO_2 in the co-gasification process. Similar results were observed from the previous research conducted by Adnan et al. [37] which concluded that an increase in the air ER will favorably lead to a decrease in the mole fraction of H_2 and an increase in the

mole fraction of CO in the syngas. Another study conducted by Pinto et al. [21] also discovered that an increase in the air ER leads to a corresponding decrease in the mole fraction of H_2 and CH_4. The ER value should be considerable reduced but high enough for the complete combustion of char [34] because too much oxygen completely oxidizes the fuel, which results in decreased yield of H_2 [35].

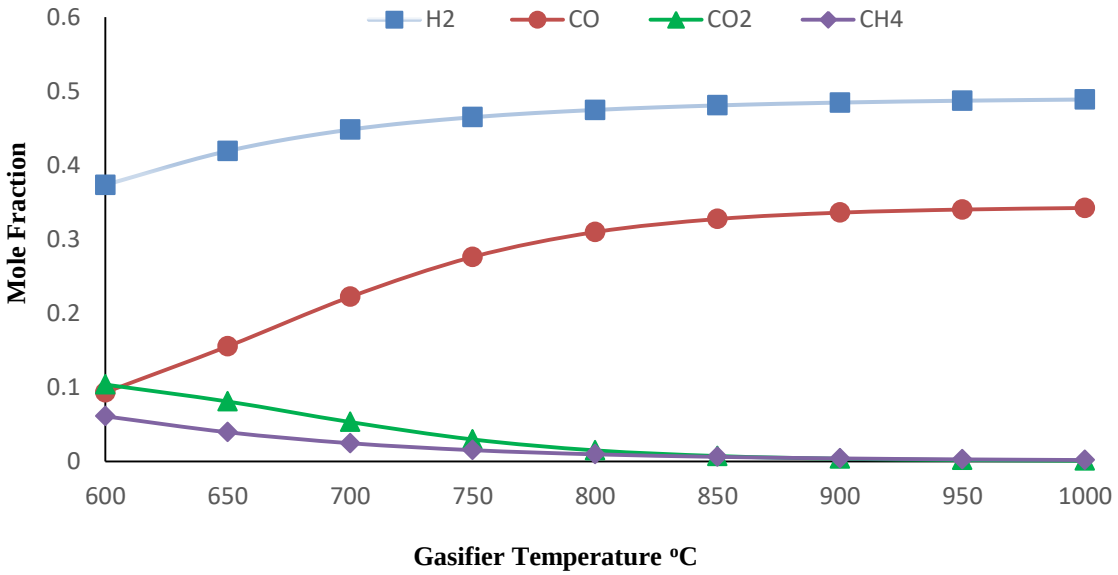

Figure 2: Effect of gasifier temperature on mole compositions of gaseous products

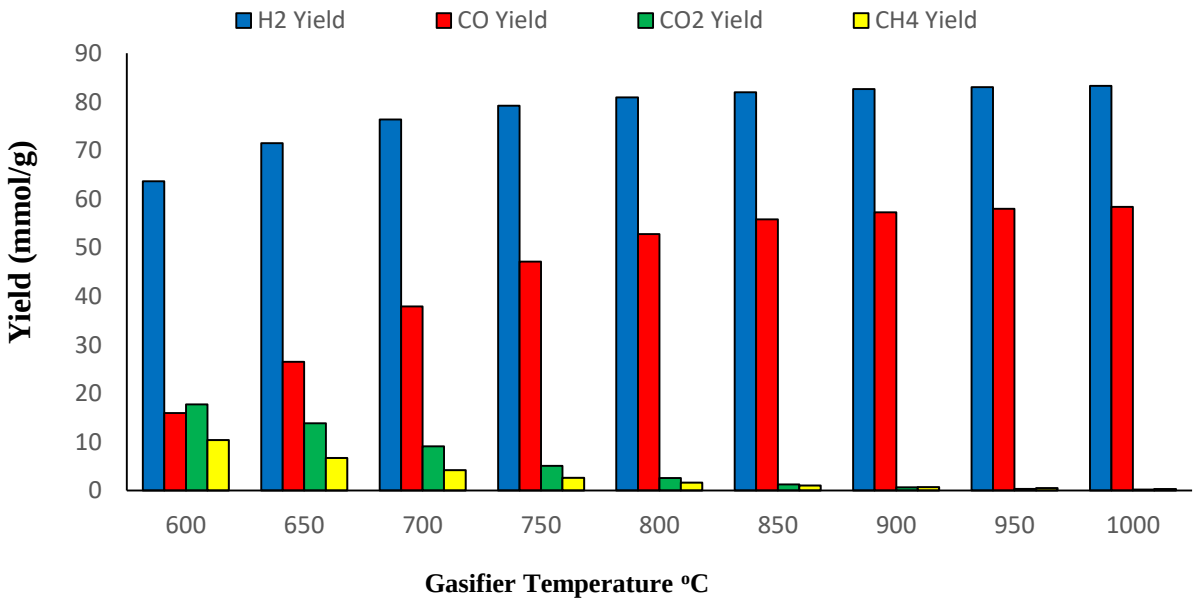

Figure 3: Effect of gasifier temperature on gaseous product yield

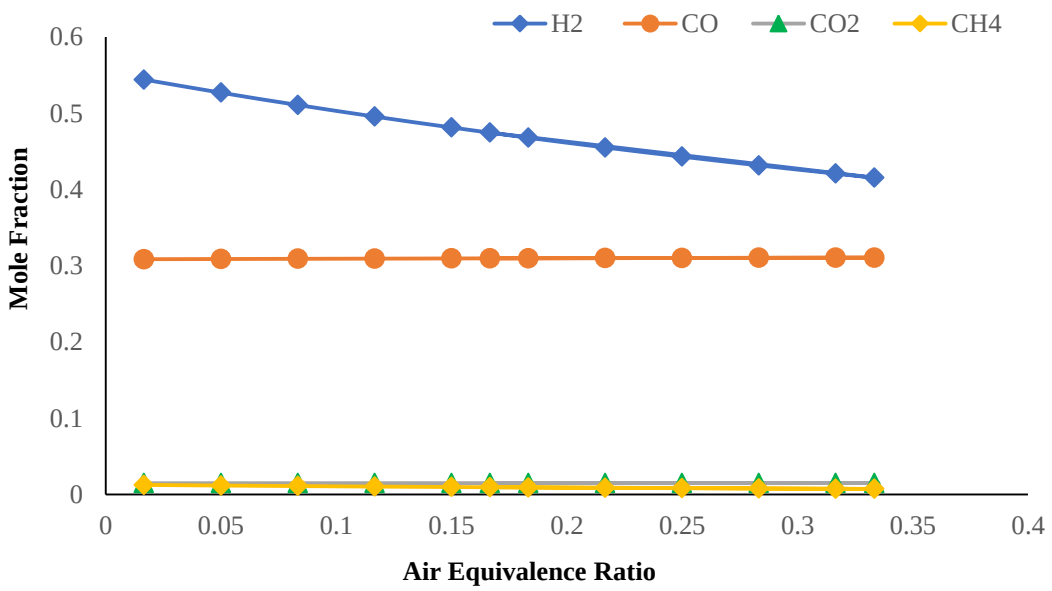

Figure 4: Effect of Air ER on mole compositions of gaseous products at temperature of 800 ^{o}C

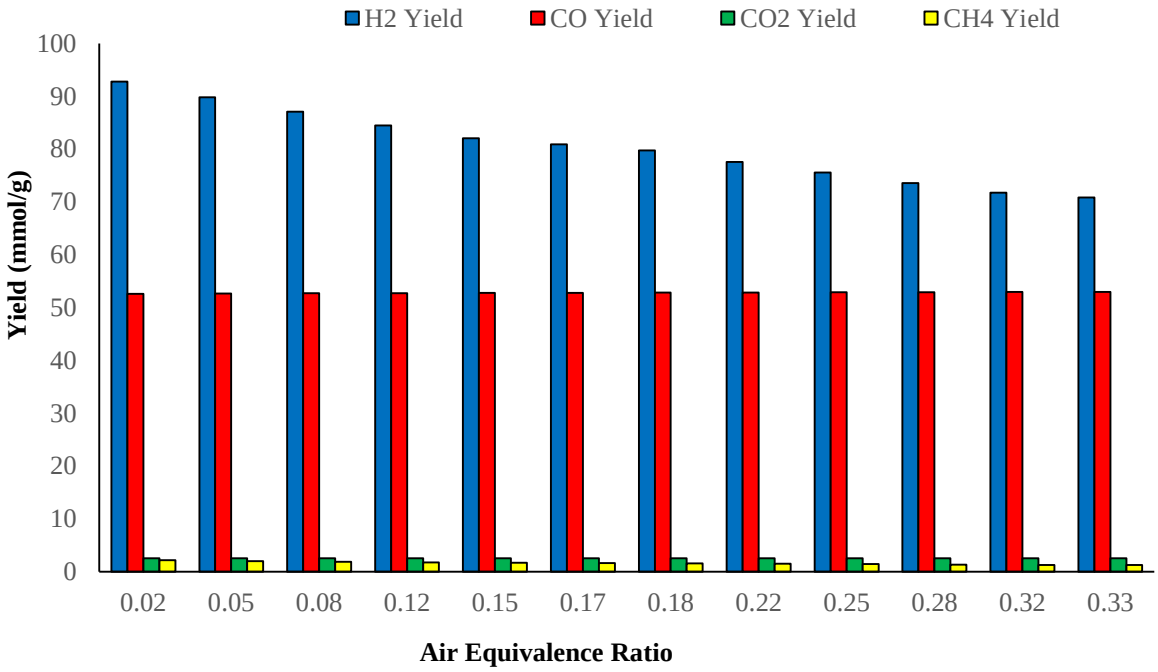

Figure 5: Effect of Air ER on yield of gaseous product yield at temperature of 800 ^{o}C

3.3 Effect of Steam -Biomass (S/B) Ratio

The presence of steam as a gasifying agent during the co-gasification process is also significant and affects the composition of the gaseous products [38]. Steam is utilized in gasifiers as a gasifying agent to improve the yield of H_2 in the gaseous product [39]. The parametric study on the influence of the S/B ratio on H_2, CO, CO_2, and CH_4 is conducted. This investigation is performed by varying the steam flow rate (100-200 kg/hr) into the gasifier at a constant feed flow rate of 300 kg/hr for both biomass, ER value of 0.17, and temperature of 800 °C.

Figures 6 and 7 displays the mole compositions and yield of H_2, CO, CO_2, and CH_4 from the co-gasification process at various S/B ratios. From Figure 6, as the S/B ratio increases, a corresponding increase in the mole fraction of CO_2 occurs as a result of the water-gas shift reaction which is favored by increased levels of H_2O in the gasifier. This reaction (Equation 3)

favours the conversion of CO into CO_2, as well as the production of additional H_2. From Figure 7, as the S/B ratio increased, H_2 yield increased from 80.89 to 81.73 mmol/g due to increased conversion, but after reaching a ratio of 0.27, the H_2 yield began to decrease from 81.73 to 80.95 mmol/g as the S/B ratio rose. This result follows the same trend with the study conducted by Ajorloo et al. [40] which concluded that to maximize H_2 production in an air-steam gasification process, the steam-to-biomass ratio should be kept low. This is to enhance the production of H_2 in the gasifier. The mole composition of CO also increased as the S/B ratio increased, but when a further increase past the value of 0.22 led to a decrease in the mole composition of CO from 0.32 to 0.26. A higher S/B ratio also resulted in lower CH_4 concentrations as seen in Figure 6. These results are in agreement with a previous study conducted by Yong and Rasid [41]. They reported that an increase in the S/B ratio leads to an increase in the mole fractions of H_2 and CO_2, while the mole fractions of CO and CH_4 decreases. An increase in the yield of CO_2 from 2.54 to 8.12 shows that the water-gas shift reaction (Equation 4) is favored by an increase in the S/B ratio [42].

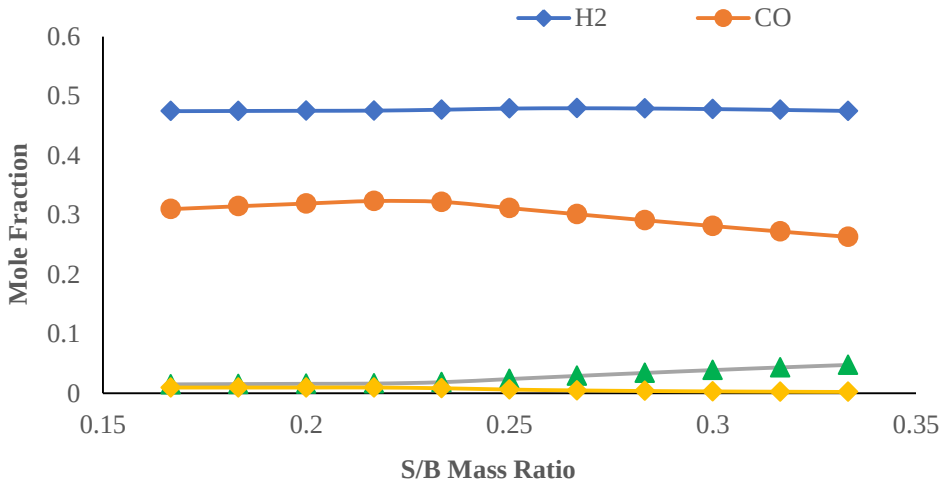

Figure 6: Effect of S/B ratio on mole compositions of gaseous products at temperature of 800 ^oC

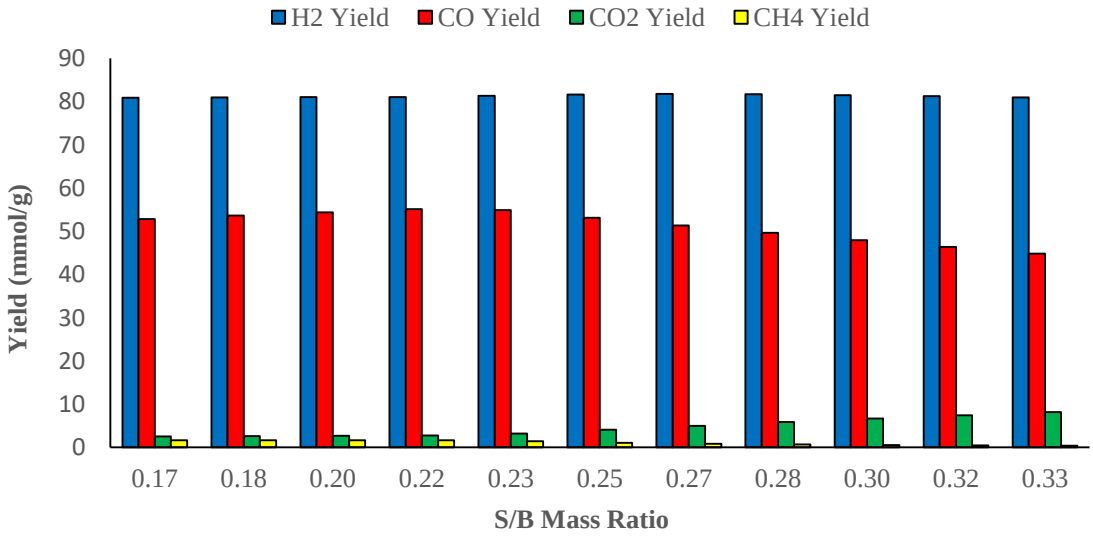

Figure 7: Effect of S/B ratio on gaseous product yield at temperature of 800 ^oC

3.4 Effect of Biomass Blending Ratio (A/P ratio)

The influence of the algae-plastic (A/P) feedstock ratio on H_2, CO, CO_2, and CH_4 products was investigated. Microalgae and HDPE were varied at ratios of 1:0, 0:1, 1:1, 2:1, 1:2, 3:1, and 1:3 respectively. The temperature was set to 800°C with air and steam flow rates at 100 kg/hr. Figures 8 and 9 shows the mole compositions and yield of the syngas (H_2, CO, CO_2, and CH_4) from the co-gasification process at different blending ratio. From Fig. 8, the mole fractions of H_2 and CO_2 experienced a decrease when the plastic content of the mixed feedstock is higher than the algae content. Higher plastic content also caused an increase in the mole fractions of CO and CH_4. The best yields of H_2 were achieved when the feedstock's microalgae content was higher than its plastic content, as shown in Fig. 9. For CO and CH_4, the maximum yield

was obtained when the algae content was less than the plastic content in the feedstock. Likewise, higher yields of H_2 and CO_2 were obtained when the ratio of algae in the feedstock was more than the plastic. The decreasing H_2 yield shown in Figure 9 could be a result of the synergistic effect between the algae and plastic reaching its limit, as the H_2:CO ratio of the produced gas is significantly influenced by the composition of organic matter in the biomass [43]. Adnan et al. [37] conducted a study to examine the relationship between the gasification performance and biomass properties. The gasification of algae produced the highest H_2/CO. The gasification of other biomasses like palm frond, rice husk, and mangrove, were used as comparisons. This trend indicates that the plastic content in the feedstock should be kept at a limit. Excessive HDPE content in feedstock hinder the radicals released from the algae biomass. This leads to a restriction on reforming reactions that improve the yield of H_2 [16]. Numerous studies have investigated the co-gasification of high-density polyethylene (HDPE) with various biomass materials. Through the application of simulations and models, these investigations offer valuable insights into the efficiency and product yields of the co-gasification process. The findings indicate that incorporating HDPE into biomass can enhance the yields of hydrogen and carbon monoxide, along with increasing the higher heating value (HHV) of the resulting gas [44-49]. Overall, the co-gasification of HDPE with biomass holds potential for enhancing both the efficiency and the quality of products derived from waste-to-energy conversion processes.

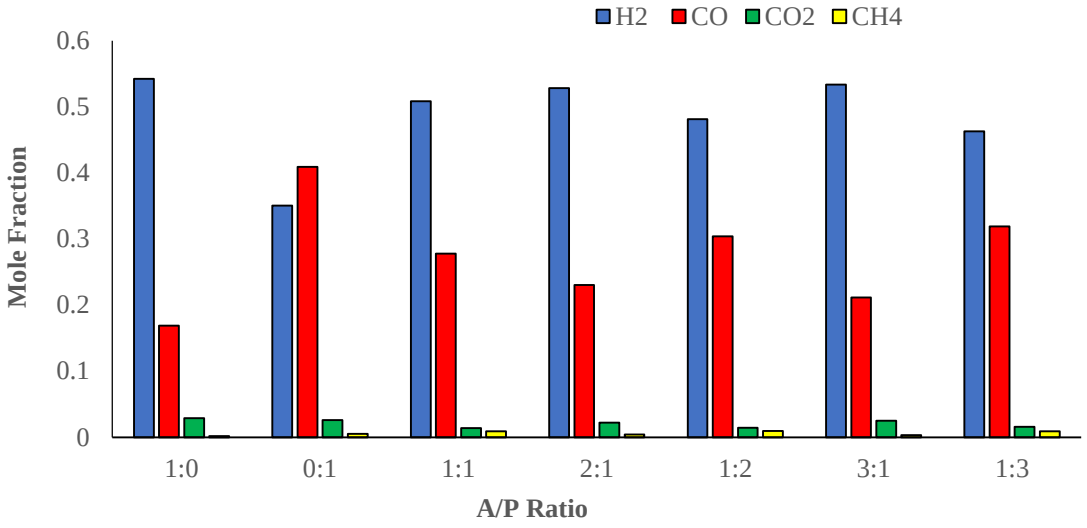

Figure 8: Effect of A/P ratio on mole compositions of the gaseous products at temperature of 800 ^oC

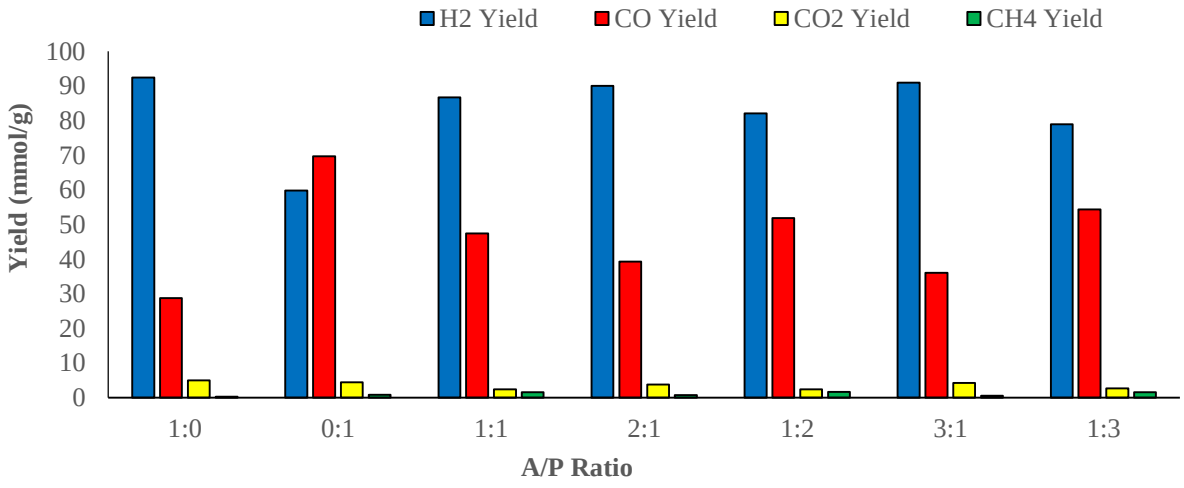

Figure 9: Effect of A/P ratio on gaseous product yield at temperature of 800 ^oC

3.5 Effect of Varying Mixture of Gasifying Agents

The influence of air and steam (gasifying agents) on the yield and composition of gaseous products is studied. For this parametric investigation, a total mass flow rate of 100 kg/hr was achieved for the gasifying agents by adjusting the mass flow rates of air (0-100 kg/hr) and steam (100-0 kg/hr) in opposite directions. Both biomasses were fed at 300 kg/hr and gasifier temperature was set to 800°C. Figures 10 and 11 depict the mole composition and yield of H_2, CO, CO_2, and CH_4 produced from the gasifier as the ratio of the gasifying agents was altered. Figure 10 shows that an increase in the flow rate of steam with a corresponding decrease in the flow rate of air led to an increase in the mole fraction and yield of H_2 and CO. A slight increase was also observed in the yield of CH_4 and CO_2 as displayed in Figure 11. Yong and Rasid [41] recent research on both steam and air gasification reported that the presence of steam in the gasifier is more favourable for the production of hydrogen-rich syngas than the presence of air. Ramzan [50] also reported that steam injection increases the yield of H_2 in the gasification process. Steam as a gasifying agent favors reforming reactions while air favors combustion reactions [51]. Therefore, a decrease in the content of air should cause a decrease in concentration of CO and CO_2, but, as the flow rate of steam is increased with a corresponding decrease in the flow rate of air, Figure 11 demonstrates higher yields for H_2, CO, CO_2, and CH_4. This pattern shows that increasing the flow rate of steam in air-steam gasification enhances the production of gaseous products while decreasing the char yield [52].

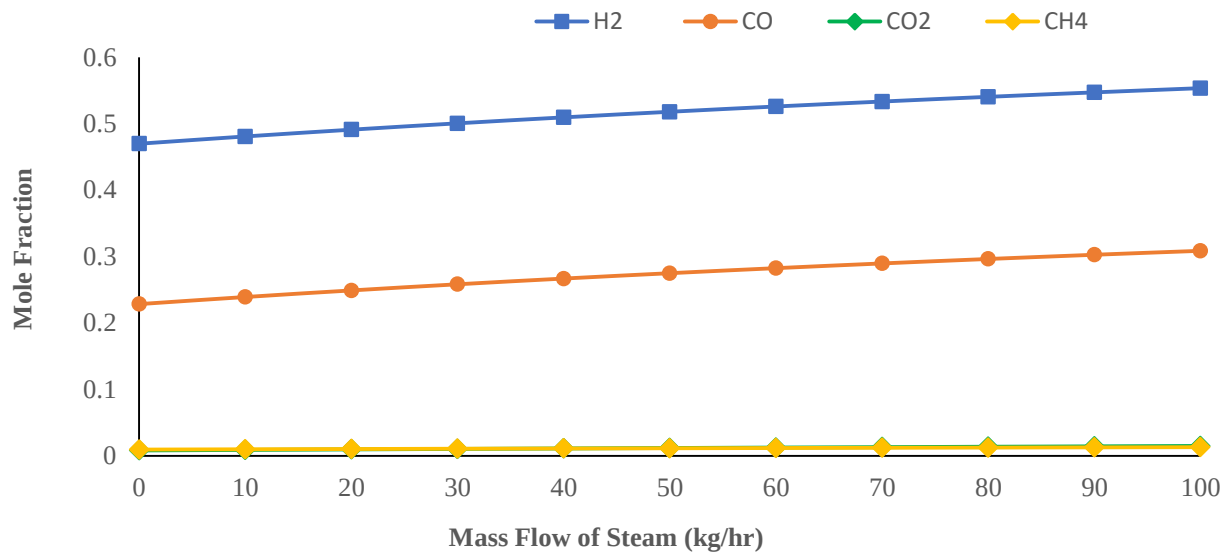

Figure 10: Effect of air-steam ratio on mole fraction of gaseous products at temperature of 800 °C

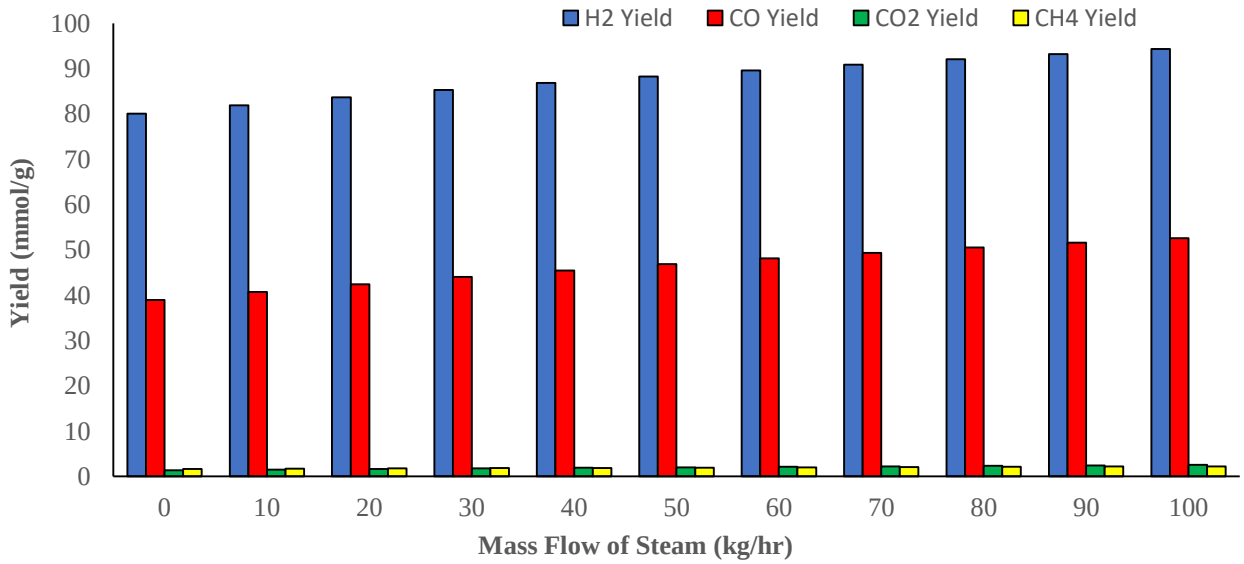

Figure 11: Effect of air-steam ratio on gaseous product yield at temperature of 800 °C

3.6 Model Validation

The built-in modules on the process simulator, Aspen Plus were used to create the base case model for the co-gasification process. To ensure the validity of this co-gasification model for the parametric study, the results (gaseous product composition) obtained from this study model was compared with the experimental data extracted from literature [53]. The steam gasification of various mixtures of biomass and waste plastic (HDPE) was carried out in continuous mode gasification at 900 °C. The results obtained from the model at 900 °C were used to compare the range of data obtained from the experimental work. Table 4 shows the data obtained from experiment (Literature) and simulation model. It is observed that the simulation results agree with the experimental data range especially for H_2 and CO. The presence of air as a gasifying agent in the simulation model favors the combustion reactions (Equation 1, 2, 9) to produce more CO. The high gasifier temperature also promotes the steam-methane and CO_2 reforming reaction (Equation 6 and 7) which further increases the yield of CO and H_2 while lowering the concentration of CO_2 and CH_4.

Table 4: Comparison results for the validation of the base model

Syngas Composition	Literature	Model
H_2	40 - 58 vol%	48.46
CO	27 - 29 vol%	33.6
CO_2	7 – 9 vol%	0.36
CH_4	3 – 18 vol%	0.407

4. CONCLUSION

This work develops a steady-state Aspen plus thermodynamic model based on Gibb's free energy minimization for the co-gasification of microalgae (*chlorella vulgaris*) and high-density polyethylene (HDPE). The results obtained from the model are valid and agree with the data from experimental work. The effect of process parameters such as gasifier temperature, air/steam ratio, steam-to-biomass ratio, biomass blending ratio, and air ER was investigated in relation to the quality (mole composition and yield) of gaseous products. According to the obtained results, increase in the gasifier temperature favours the yield of CO and H_2 owing to the steam-forming reaction and boudouard reaction. The yield of CH_4 and CO_2 decreased with increasing temperature as a result of the reverse-methanation and water-gas shift reaction. Increased air flow rate in the gasifier enhances exothermic reactions such as combustion and oxidation, resulting in an increase in CO and CO_2. Lower ER values were seen to have favoured the formation of H_2. Furthermore, the effect of microalgae on syngas production was observed when the concentration of H_2 peaked at an S/B ratio of 0.27 when steam was used. The mixture ratio of biomass-plastics was altered to improve the synergistic effects on syngas production. Higher yields of H_2 occurred when the microalgae content in the feedstock was more than the plastic content. Increased steam flow rate in the gasifier while decreasing air flow rate resulted in increased gaseous product production. The results of this model will serve to consolidate researches on co-gasification of biomass-plastic. On the other hand, this work shows the effect of substituting fossil fuel sources of energy to ensure energy and environmental sustainability.

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