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The Study of Torrefaction in Air and Steam Biomass Gasification for Syngas Production Through Process Simulation

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Abstract. Torrefaction is a process where biomass is converted to solid biofuel that can be sustainably used for energy generation to produce syngas. Limited information was found for a system with the combination of torrefaction and gasification. Therefore, a study by using a thermodynamic tool was conducted to study the best conditions of such system for empty fruit bunch (EFB). Four case studies were conducted for air gasification with and without torrefaction as Cases 1 and 2 respectively, steam gasification with and without torrefaction as Cases 3 and 4 respectively with varying equivalence ratio (ER), and steam-to-biomass (S/B) ratio applied in a process simulation model that is thermodynamic-based. It was found that the best case is Case 3 which increases the syngas concentration and higher heating value (HHV) by 4% and 0.4%, respectively, compared to Case 1. Therefore, steam gasification with torrefaction is the best method for syngas production.

INTRODUCTION

Malaysia produces many oil palm waste that includes empty fruit bunch (EFB), mesocarp fibre (MF), oil palm trunk (OPT), oil palm frond (OPF), and palm kernel shell (PKS) due to its focus on the oleochemical field and oil palm plantation. Sadly, only a small amount of the biomass is reused for either power generation of the plant or paper production, which indicates that the rest are often left wasted; so this renewable energy source shall be reused [1-3].

Biomass exhibits some advantages that make it superior to some energy sources, including its low sulfur content that helps reduce greenhouse gas emissions, sustainability, and is cheap [4]. Biomass is often used for some processes that can be categorized into two: thermochemical and biochemical routes. Thermochemical processes like liquefaction, combustion, pyrolysis and gasification are often prioritized due to their shorter reaction time and higher efficiency [5]. Gasification is a process that gasifies biomass under the influence of gasifying agents like air or steam at a temperature of more than 700 °C to produce syngas that comprises hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), and methane (CH_4) [6]. Hydrogen gas is an indication in evaluating the process since it is one of the best energy carriers as it releases no carbon during power generation [7]. Therefore, steam gasification, which can produce high H_2 concentration in the product gas, has been given high attention [8].

Raw biomass has some drawbacks that must be overcome before usage, including high moisture content and moisture uptake that increases the difficulty in transportation and storage, not to mention the higher risk of biological degradation causing the loss of cost. The poor grindability also will increase the grinding cost of the biomass. These disadvantages have caused the industry to reconsider applying biomass in daily energy production [9-11]. To curb this problem, pre-treatment is needed.

Torrefaction as one of the best options provides an effective way to reduce the moisture content and improve the calorific value of the biomass by heating the biomass at a temperature of 200-300 °C with external heating under the

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influence of air or oxygen [12-14]. Some studies have been conducted on a combination of gasification and torrefaction. Prins et al. conducted research related to torrefied and raw wood where the torrefied wood has better performance and efficiency [15]. Research conducted by Bach et al. related to torrefaction and gasification for spruce wood branches found that the product lower heating value (LHV) is improved via torrefaction[16]. A combination of torrefaction and gasification experimental work was done by Li et al. on EFB but steam gasification that combined with torrefaction operating at solely 300 °C temperature. There has been little information regarding EFB in a system that combines torrefaction and gasification and compares the performance of air and steam gasification to investigate the aspects that would leave impacts on the syngas production which acts as an energy source for some processes. So, the objective of this study was to simulate the effect of torrefaction for EFB towards the gasification process that aims to produce syngas with high HHV and syngas concentrations.

METHODOLOGY

Description of the Model

As shown in Figure 1, the model was built with the combination of torrefaction and gasification processes similar to the previous work[17]. The fuel properties of the raw biomass were adopted from other work, as shown in Table 1, including moisture content (MC), fixed carbon (FC), volatile matter (VM) and ash of proximate analysis, and carbon (C), oxygen (O), hydrogen (H) and nitrogen (N) of ultimate analysis. After drying of the raw EFB, which minimises the moisture content in RStoich DRYER to 1%, torrefaction, as shown in red box was conducted in RYield YIELD reactor under inert atmosphere flowing at 10 mL/min of nitrogen gas to form torrefied EFB and volatile matter, which the temperature was controlled at 250 °C at atmospheric pressure. Conversion of torrefied EFB into various atoms as shown in Table 1 was done in the RYield DECOM reactor. The decomposed feed was then fed into RGibbs GASIFIER to react with air or steam (blue box) at 800 °C under atmospheric pressure to produce syngas that consisted of H_2, CO, CH_4 and CO_2.

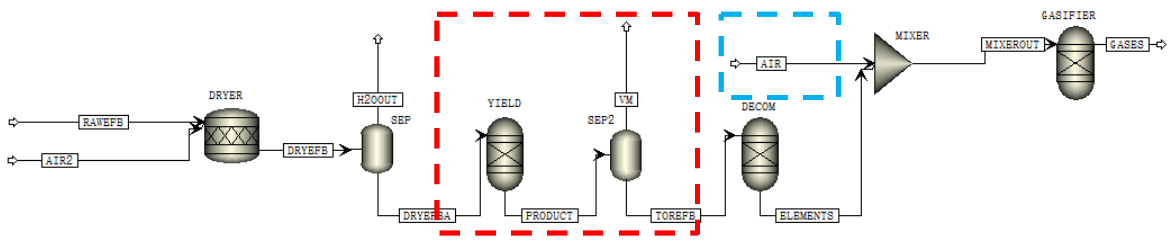

FIGURE 1. Aspen Plus flow diagram of the case studies with red box showing the torrefaction process while blue box showing the type of gasifying agents.

TABLE 1. Ultimate and proximate analysis of raw EFB.

	Proximate Analysis (wt % Dry)				**Ultimate Analysis (wt % Dry Ash Free)**				**HHV (MJ/kg)**
	MC	FC	VM	Ash	C	H	N	O	
Raw EFB	6.55	10.23	80.11	3.11	42.82	6.07	0.54	50.57	17.57

Model Assumptions

The simulation assumptions were similar to those reported in our earlier work [17]. The higher heating value (HHV), which is the heat amount produced by dry combustible species in the gas product after gasification, was calculated using Equation 1[19]:

$$HHV\ (MJ/Nm^3) = \frac{12.76\ (vol\%\ H_2) + 12.63\ (vol\%\ CO) + 39.76\ (vol\%\ CH_4)}{100} \tag{1}$$

Cold gas efficiency (CGE) was calculated as shown in Equation 2 [20]:

$$CGE\ (\%) = \frac{v_g HHV_g}{\dot{m}_f HHV_f} \times 100 \tag{2}$$

where $\dot{m}_f$ is the fuel mass low rate (kg/s), v_g is the gas flow rate (m^3/hr), while HHV_f and HHV_g are the heating values of fuel (MJ/kg) and gas (MJ/Nm^3) respectively.

Case Study Description

To optimize the production of syngas from EFB, some case studies were run during the research with the combination of torrefaction pre-treatment and gasification.

Case 1

Torrefaction was conducted under an inert atmosphere at 250 °C for 30 minutes at atmospheric pressure, with the gas product of torrefaction purged, and gasification was carried out under the influence of air and Equivalence Ratio (ER) of 0.2 to 0.4 at 800 °C and 1 atm. Sensitivity analysis executed was to determine ER effects on syngas production and HHV.

Case 2

Based on Figure 1, the torrefaction reactor and its separator in the red box were removed to test the effects on syngas production, as raw EFB contains higher volatile matter that might produce a higher amount of H_2 and CO.

Case 3

Steam replaced air as a gasification medium, as shown in the blue box of Figure 1, as higher syngas concentration might be achieved using steam gasification. In order to investigate the relationship between syngas concentration and S/B ratio, sensitivity analysis was conducted at steam-to-biomass (S/B) ratio from 0.3 to 2 with gasifier temperature of 800 °C and 1 atm.

Case 4

Steam gasification was conducted similar to Case 3, but the torrefaction reactor and separator in the red box were removed to determine the importance of torrefaction in the combined torrefaction and steam gasification system.

The summary of case studies is as shown in Table 2.

TABLE 2. Case studies summary.

Case Study	Presence of Torrefaction (250 °C 30 minutes 1 atm)	Gasifying Agent (800 °C 1 atm)
1	Yes	O_2
2	No	O_2
3	Yes	Steam
4	No	Steam

RESULTS AND DISCUSSION

Validation of Model

The comparison was made for the torrefaction products' yield, which exists in the form of solid, liquid, and gas between simulated results of this work and previous experimental works from literature [18, 21] for the accuracy of model validation, as shown in Figures 2 and 3. The comparison was made based on experimental torrefaction conducted at a temperature of 250 °C for 30 minutes of residence time with atmospheric pressure for EFB. In Figure 2, the simulated yield is very similar to the actual yield from the experiment because of the properties of the yield-based model. As for Figure 3, the error of the simulated yield is acceptable compared to experimental yield, especially the H_2 and CO yield, where the error was only 4.54% and 2.34%, respectively. Therefore, the final simulation results were in the acceptable range, which showed that the model was reliable.

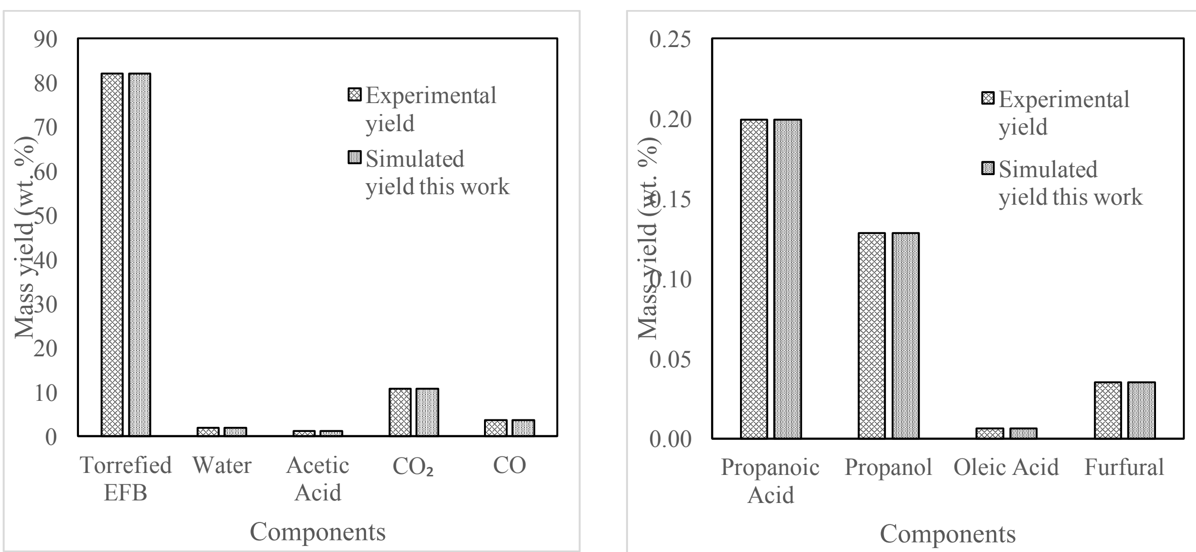

FIGURE 2. Comparison of product yield between literature data and this work in terms of torrefied EFB and volatile product mass yield.

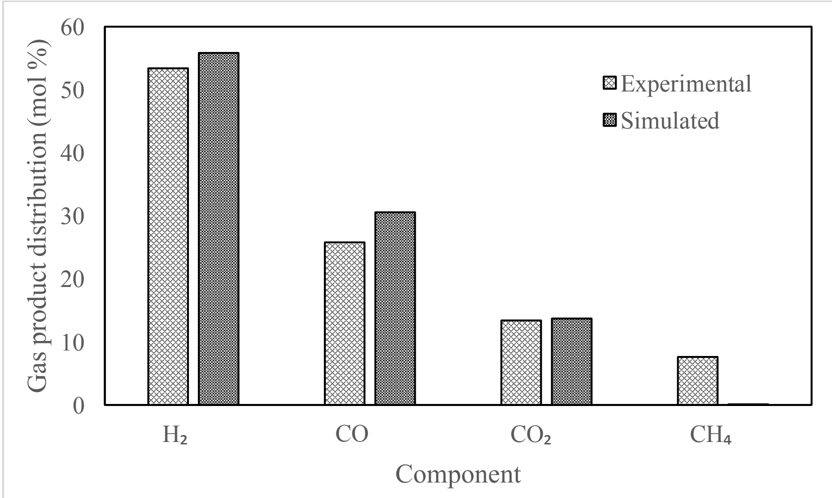

FIGURE 3. Syngas yield comparison between literature and this work.

Effects of Equivalence Ratio (ER)

To obtain high HHV, syngas production and CGE, the influence of ER along with the effect of torrefaction was investigated. Figures 4 and 5 show the effects of ER on syngas production in air gasification. The decreasing trend of H_2 but increasing CO against ER might be due to the faster oxidation reaction that increases the carbon conversion than the cracking reaction, causing more CO and CO_2 produced than H_2 [22-23]. As for HHV and CGE, the ER increase caused a decrease in HHV as shown in Figure 6, while in Figure 7, CGE increased with ER, similar to the trend reported by Liu et al. [24]. However, when the comparison is made between Cases 1 and 2, it can be observed that the H_2 concentration of Case 1 is higher than Case 2 but vice versa for CO concentration. This might be due to the loose structure of the torrefied biomass caused by the decomposition of hemicellulose and lignin during the torrefaction process that facilitated the emission of the gases [25]. Therefore, the improvement of syngas concentration enhanced the HHV of the syngas in Case 1 compared to Case 2. The CGE of Case 2 is higher than Case 1 in Figure 7. This might be due to the higher amount of gases produced in Case 2 that contributed to a higher amount of energy respective to the energy of the biomass.

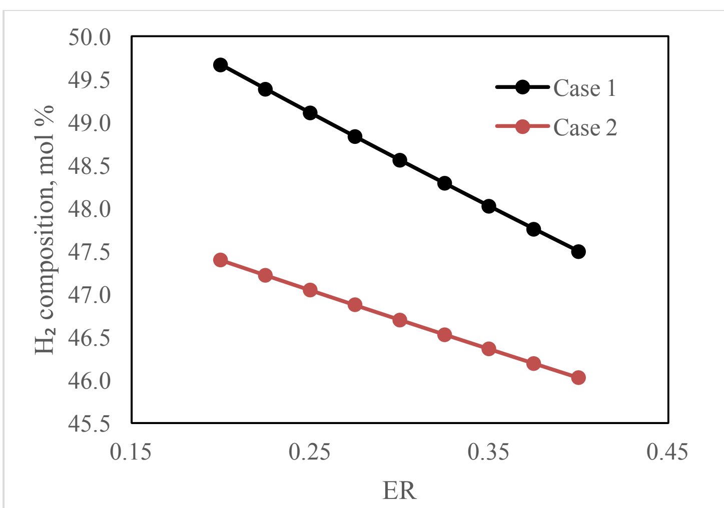

FIGURE 4. H_2 concentration against ER of different cases.

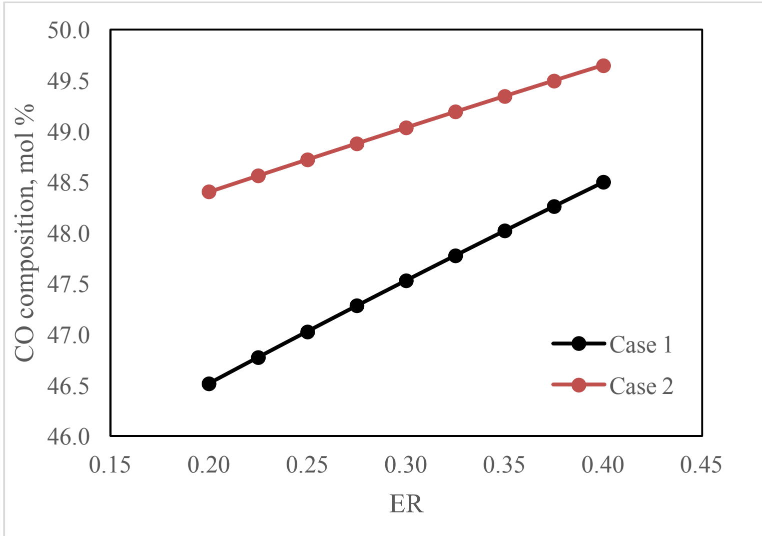

FIGURE 5. CO concentration against ER of different cases.

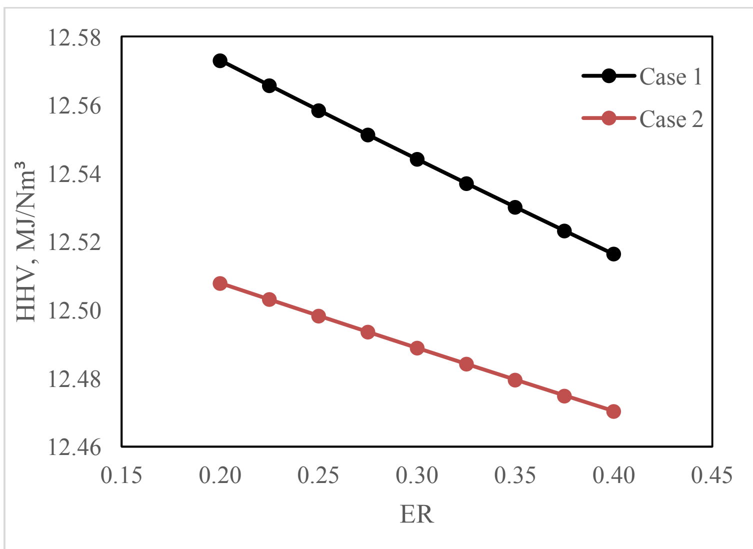

FIGURE 6. HHV of Cases 1 and 2 against ER.

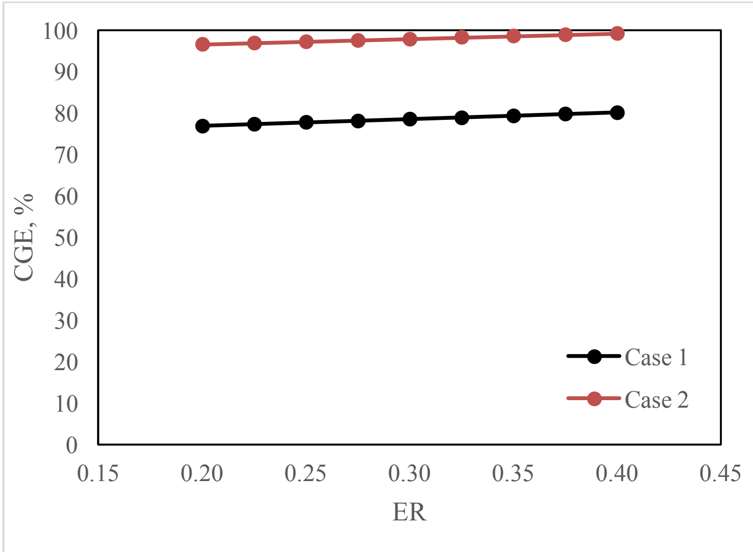

FIGURE 7. CGE of Cases 1 and 2 against ER.

Effects of Steam to Biomass (S/B) Ratio

Theoretically, higher H_2 concentrations can be achieved with the usage of steam gasification [26]; therefore, the air was replaced with steam as a gasification medium in the gasifier. Figures 8 to 11 show the effects of the S/B ratio on syngas composition, HHV, and CGE, respectively. The introduction of steam into the gasifier caused the H_2 concentration to increase, which might be due to water gas and water gas shift reactions [27]. The HHV decreased against the S/B ratio due to the massive loss of CO concentration. This is caused by a water gas shift reaction which increased H_2 content with the expense of CO [28]. Besides, CGE slightly decreased when the S/B ratio increased as CO concentration decreased syngas' HHV, therefore lowering the CGE obtained [29]. When comparing Cases 3 and 4, the higher amount of char in torrefied EFB produced through the devolatilization reaction in torrefaction promoting the water gas reaction between char and steam, causing the H_2 concentration of Case 3 to be higher at a higher S/B ratio [30]. As for CO concentration, Case 3 is higher overall due to the higher char content in torrefied biomass promotes reverse Boudouard and water-gas reaction [31]. The HHV of syngas is deeply affected by H_2, CO, and CH_4 as shown in Equation 1; therefore, the higher concentration of both H_2 and CO produced in Case 3 leads to higher HHV across all S/B ratios. Case 3 has a slightly higher CGE compared to Case 4 but the difference is insignificant.

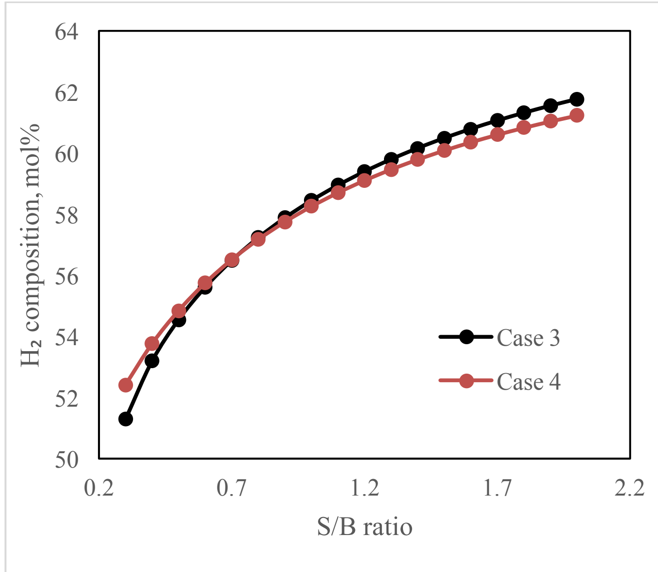

FIGURE 8. H_2 concentration against S/B ratio of different cases.

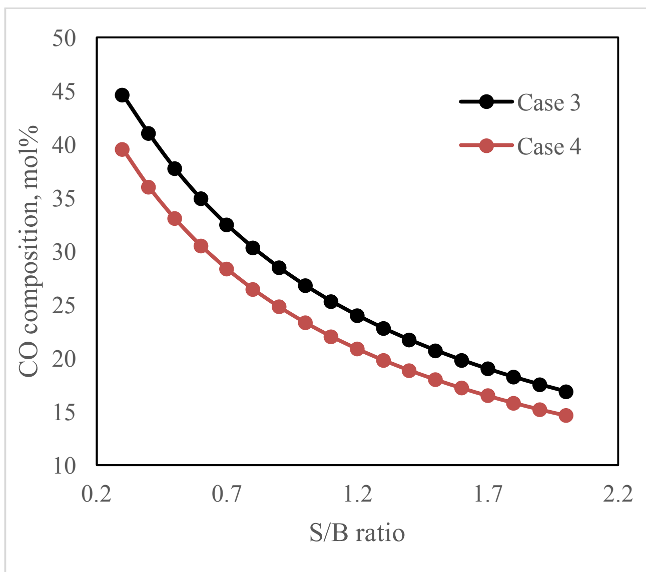

FIGURE 9. CO concentration against S/B ratio of different cases.

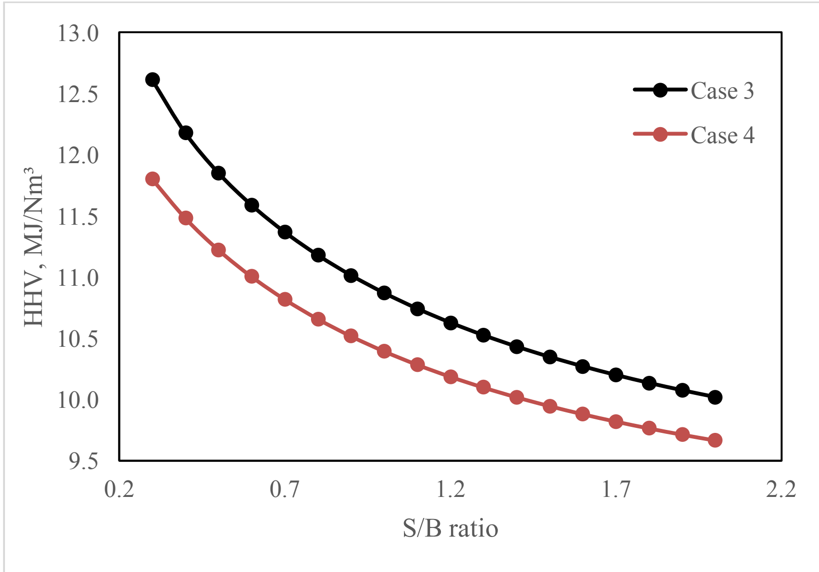

FIGURE 10. HHV of Cases 3 and 4 against S/B ratio.

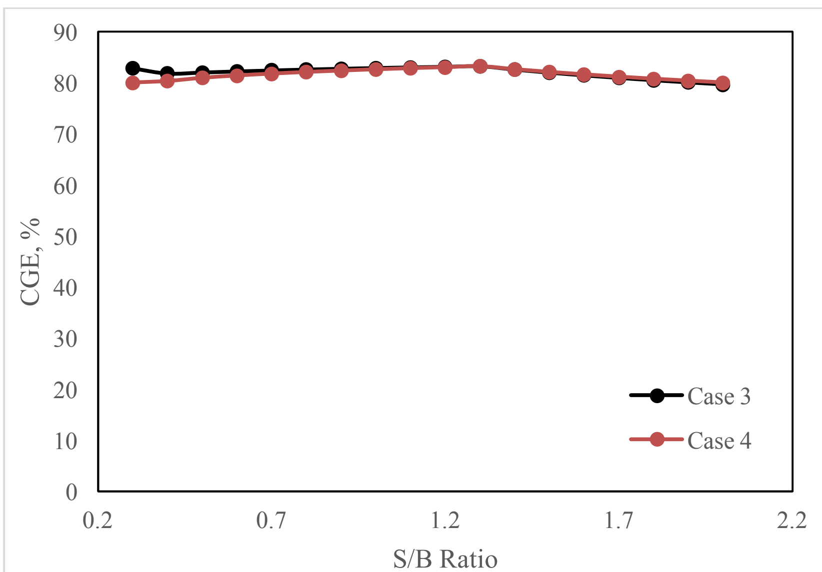

FIGURE 11. CGE of Cases 3 and 4 against S/B ratio.

Comparison of Case Studies

Figures 12 and 13 show the maximum achievable H_2 and CO concentration among the case studies in this work, respectively. It is worth noting that steam gasification of Cases 3 and 4 has a better production of H_2 where the maximum achievable concentration is higher than air gasification of Cases 1 and 2 by 1.24 fold but lower production of CO, which is because of the water-gas shift reaction where the CO reacts with steam to produce H_2, resulting in lower CO concentration [32].

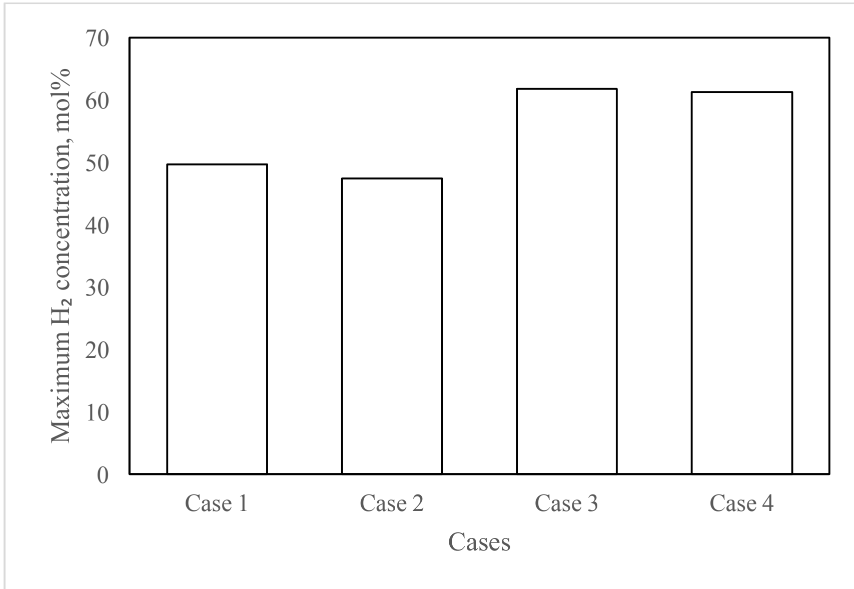

FIGURE 12. Maximum H_2 concentration of all cases.

FIGURE 13. Maximum CO concentration of all cases.

Case 1 is proven to have an average HHV compared to Case 2 and Case 3, where the highest was achieved by Case 3, as shown in Figure 14. This shows that H_2 and CO concentrations have a major influence on the heating value of syngas. As for CGE, the highest is achieved by Case 2. This can be observed in Figure 15, and this situation might be due to the HHV of the syngas produced is very close to that of the raw biomass.

FIGURE 14. Maximum HHV of all cases.

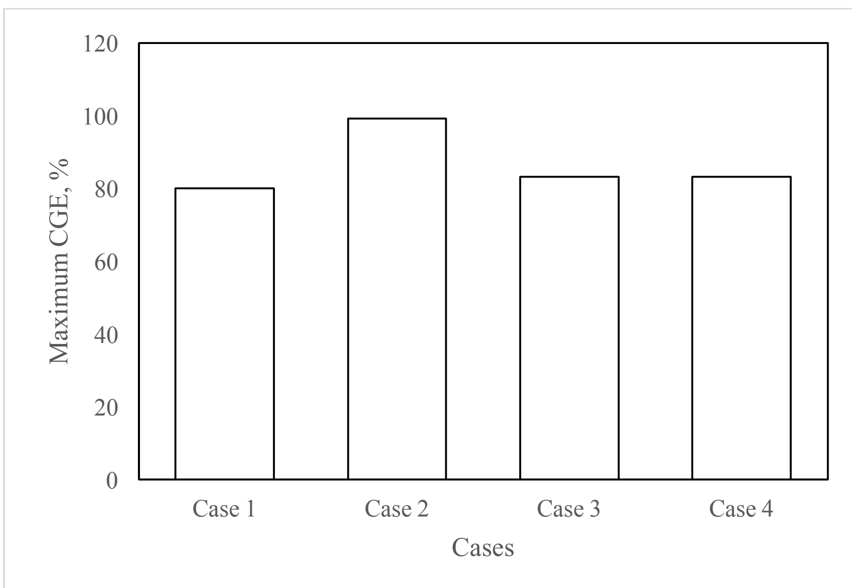

FIGURE 15. Maximum CGE of all cases.

CONCLUSION

The combined torrefaction and gasification Aspen Plus model was developed for oil palm residue, which is EFB. To obtain maximum syngas concentration, ER needs to be minimized, the S/B ratio needs to be maximized, and torrefaction needs to be introduced to the system. The best case is Case 3, where HHV and syngas concentrations are higher than Case 1 by 0.4% and 4%, respectively while achieving relatively high CGE. Furthermore, the introduction of torrefaction increases the efficiency of the gasifier in terms of the quality of the syngas produced, proving that torrefaction is an effective pre-treatment method.

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