Energy, exergy and environmental analyses of conventional, steam and CO_2-enhanced rice straw gasification

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Abstract

In this study, air, steam and CO_2-enhanced gasification of rice straw was simulated using Aspen Plus^{TM} simulator and compared in terms of their energy, exergy and environmental impacts. It was found that the addition of CO_2 had less impact on syngas yield compared with gasification temperature. At lower CO_2/Biomass ratios (below 0.25), gasification system efficiency (GSE) for both conventional and CO_2-enhanced gasification was below 22.1%, and CO_2-enhanced gasification showed a lower GSE than conventional gasification. However at higher CO_2/Biomass ratios, CO_2-enhanced gasification demonstrated higher GSE than conventional gasification. For CO_2-enhanced gasification, GSE continued to increase to 58.8% when CO_2/Biomass was raised to 0.87. In addition, it was found that syngas exergy increases with CO_2 addition, which was mainly due to the increase in physical exergy. Chemical exergy was 2.05 to 4.85 times higher than physical exergy. The maximum exergy efficiency occurred within the temperature range of 800 ^oC to 900 ^oC because syngas exergy peaked in this range. For CO_2-enhanced gasification, exergy efficiency was found to be more sensitive to temperature than CO_2/Biomass ratios. In addition, the preliminary environmental analysis showed that CO_2-enhanced gasification resulted in significant environmental benefits compared with stream gasification. However improved assessment methodologies are still needed to better evaluate the advantages of CO_2 utilization.

Keywords: CO_2-enhanced gasification, Conventional gasification, Energy analysis, Exergy analysis, Environmental analysis, Biomass

1 Introduction

Energy has become increasingly crucial for industrial sector worldwide. The utilization of energy has direct influence on energy consumption and environmental impacts [1]. The sustainable use of energy is one of the most important challenges that industries have to deal with nowadays. To address these challenges, energy, exergy and environmental analysis have been considered as effective tools for the assessment of the impacts of industrial processes [1, 2], based on which solutions towards sustainable utilization of resources can be created.

Generally speaking, gasification is an attractive thermochemical conversion technology for the recovery of energy from biomass [3, 4]. In a gasification system, biomass is converted to syngas, the composition of which depends on several factors, such as biomass properties, gasification technology and gasifying agent used. However, it is still of big challenge for the large scale utilization of biomass due to its low volumetric energy density [5]. Thus, the development of sustainable and energy efficient biomass conversion processes are vital to promote the utilization of biomass as an alternative energy source.

In conventional gasification processes, air, oxygen, steam, and/or a mixture of these are commonly used as oxidizing agents. The air gasification of biomass generates syngas of low heating value, which can be used for the generation of heat and power [6, 7]. Normally, the use of pure oxygen and steam as gasifying agents can result in syngas with higher heating value. However, the use of pure oxygen is not favourable for biomass gasification due to the significant capital cost required. It is also reported that the use of steam as the gasifying agent showed better performance than the use of air and oxygen as gasifying agents [8, 9].

Recently, due to the concerns on CO_2 mitigation, the use of carbon dioxide (CO_2) as an oxidizing agent in biomass gasification has become a new frontier for the research on biomass conversion as well as CO_2 utilization. Much effort has been made on biomass gasification using CO_2 as a gasifying agent [10-16] which mainly focuses on the study of gasification reactivity [11, 17] and gasification characteristics [12, 18] in general. It is reported that the addition of CO_2 in gasification process has shown many advantages such as greater syngas yield and the capability of tuning its composition for different applications [10, 14]. CO_2-enhanced gasification has also demonstrated benefits such as the elimination of water gas shift process and energy intensive gas cleaning process. Thermodynamic analysis of biomass gasification using steam or air as gasifying agent had been carried out by many researchers [19-22], the results of which demonstrated the benefits of these processes in the design and optimisation of energy efficient process. However, not much research on thermodynamic analysis of CO_2 gasification of biomass has been conducted [10, 23]. In order to improve the design of efficient biomass-based gasification process using CO_2 as the gasifying agent, it is essential to understand such processes in terms of energy, exergy and environmental impacts.

Exergy analysis is an interdisciplinary concept that combines energy, environment and sustainable development notions [24, 25], and has been used to identify opportunities for process improvement and to evaluate different process alternatives [2, 26]. Recently, exergy analysis of biomass-gasification based process has attracted much attention due to the potential of biomass as a feedstock or an energy resource [3, 27-30]. Many researchers [27, 31, 32] performed exergy analysis to examine gasification performance of different types of biomass and benchmark with respect to coal gasification. A comparative study of exergy analysis of biomass gasification with steam/air [9] showed that the use of steam as gasifying agent resulted in a higher exergy efficiency. Although exergy analysis is a useful tool for evaluating the effectiveness of energy conversion processes, its application in CO_2-enhanced biomass gasification is hardly explored. Therefore, further investigation on this matter is needed [24].

Life Cycle Assessment (LCA) is a commonly adopted method for the evaluation of environmental impacts associated with all stages of a process or a product [3, 33]. It is also be used to assess the environmental impacts of biomass gasification process [3, 34-36] by evaluating all CO_2 related inputs and outputs of the system. However, not much research on the environmental analysis of CO_2-enhanced biomass gasification has been carried out based on LCA approach.

In this study, energy and exergy analyses were conducted to compare the performance of conventional and CO_2-enhanced gasification of rice straw. Environmental analysis was also carried out using SimaPro software to evaluate and compare these two gasification options in terms of their environmental impacts.

2 Methodology

2.1 Feedstock selection

In this study, rice straw was used as the biomass feedstock. Its basic properties are listed in Table 1 [13, 37].

2.2 Biomass gasification process

The simulation of biomass gasification was conducted using Aspen Plus^{TM} software (Aspen Tech Inc., USA). Proximate and ultimate analyses data and LHV of the biomass are the inputs of the gasification model. The mass and energy balance obtained using Aspen Plus^{TM} form the basis for the energy, exergy and environmental analysis. In this work, the gasifier simulation was separated into two reactors (RYield and RGibbs). Firstly, biomass stream enters the Decomposer (RYield) block, which converts the non-conventional solid into fundamental elements (C, H, O, N, S, moisture and ash). This is not a true stand-alone reactor but integral part of the gasification reactor. The output from the Decomposer block combined with oxidizing agents (steam and CO_2) is then fed to the Gasifier (RGibbs) block. Accordingly, it generates the gas products (CH_4, H_2, CO, CO_2, NH_3, H_2O, H_2S, and N_2) which exist in the gasifier outlet stream.

In addition, it was assumed that ash was discharged into the environment at ambient temperature. Details of this gasification model are explained elsewhere [5, 10, 28, 38-41]. General schema of the biomass gasification process is illustrated in Figure 1. The separation of gases and ash was carried out using a Separator (SSplit) unit and the exit gas was syngas, which was ready for further applications. The model developed in this study was validated using data published by many other researchers [28, 40, 41]. It was found that the model showed a good agreement with what were reported by others with a deviation in the range of 4% to 9%.

In this study, it was assumed that 40,000 kg/h of biomass was fed into the gasification system. The operating pressure and temperature were assumed to be 25 °C and 1 atm, respectively. Usually, fluidized bed biomass gasification is operated at a temperature in the range of 750 - 1100 °C and the corresponding oxidizing agent/biomass mass ratio is 0.30 - 0.40. In this study, a fluidized bed gasifier was adopted. Steam was considered as the main gasifying agent used in conventional gasification process due to its good gasification performance [8, 9], which was used as a benchmark for the evaluation of CO_2-enhanced gasification. The flow rate of steam (150 °C and 5 atm) was 12,000 kg/h, while the flow rate of CO_2 (25 °C and 1 atm) was 10,000 kg/h. The gasifier was operated at 1 atm and 900 °C.

2.3 Gasification reaction analysis

The main gasification reactions under steam and CO_2 atmosphere are shown below:

Reverse Boudouard reaction (RBD):

$$C + CO_2 \longleftrightarrow 2CO \qquad \Delta H_r^0 = +\ 172\ \text{MJ/kmol} \qquad (1)$$

Steam reforming (SR):

$$C + H_2O \longleftrightarrow CO + H_2 \qquad \Delta H_r^0 = +\ 131\ \text{MJ/kmol} \qquad (2)$$

Partial Oxidation (PO):

$$2C + O_2 \longleftrightarrow 2CO \qquad \Delta H_r^0 = -221 \text{ MJ/kmol} \qquad (3)$$

Water gas shift reaction (WGS):

$$CO + H_2O \longleftrightarrow CO_2 + H_2 \qquad \Delta H_r^0 = -41 \text{ MJ/kmol} \qquad (4)$$

Methane formation (MF):

$$C + 2H_2 \longleftrightarrow CH_4 \qquad \Delta H_r^0 = -74 \text{ MJ/kmol} \qquad (5)$$

Methane reforming (MR)

$$CH_4 + H_2O \longleftrightarrow CO + 3H_2 \qquad \Delta H_r^0 = +206 \text{ MJ/kmol} \qquad (6)$$

$$CH_4 + 2H_2O \longleftrightarrow CO_2 + 4H_2 \qquad \Delta H_r^0 = +165 \text{ MJ/kmol} \qquad (7)$$

2.4 Exergy analysis

Exergy balance for the above-mentioned system can be expressed as [9, 42]:

$$\dot{E}x\_biomass + \dot{E}x\_agent + \dot{E}x\_heat = \dot{E}x\_gas + \dot{E}x\_loss + \dot{E}x\_destruction \qquad (8)$$

where, $\dot{E}x\_biomass$, $\dot{E}x\_gas$ and $\dot{E}x\_heat$ denote the existence of exergy rates in biomass, product gases and heat delivered to gasifier, respectively. Meanwhile, $\dot{E}x\_agent$ represents exergy rates of oxidizing agents in gasification process. $\dot{E}x\_agent$ depicts the exergy rate in the steam in conventional gasification and represents exergy rates for both steam and CO_2 in CO_2-enhanced gasification. The exergy loss rate and destruction rate from the system are expressed by $\dot{E}x\_loss$ and $\dot{E}x\_destruction$, respectively.

By neglecting the kinetic and potential energy of a stream, the total exergy in a stream can be calculated by the summation of physical ($\dot{Ex}^{Phy}$) and chemical exergy rate ($\dot{Ex}^{Che}$) of the stream [9, 43] which can be expressed as:

$$\dot{Ex} = \dot{Ex}^{Phy} + \dot{Ex}^{Che} \qquad (9)$$

Physical exergy rate, chemical exergy rate and their standard parameters have been well-described elsewhere [9, 28, 43, 44].

On the other hand, biomass exergy rate is written as [9]:

$$\dot{Ex}\_biomass = \beta \cdot \dot{m} \cdot LHV_{biomass} \qquad (10)$$

where, $\dot{m}$ is biomass flow rate (kg/s), β is the ratio between chemical exergy and LHV of the organic fraction of biomass, and $LHV_{biomass}$ (kJ/kg) is the low heating value of biomass.

The value of β can be determined using Eq. (11) by correlating the mass fractions of Carbon(C), Hydrogen(H), Nitrogen (N) and Oxygen(O) of the biomass [9, 27].

$$\begin{aligned}\beta = {} & [1.044 + 0.0160 \times H/C - 0.3493 \times (O/C) \times (1 + 0.0531 \times H/C) \\ & + 0.0493 \times N/C]/(1 - 0.4124 \times O/C)\end{aligned} \qquad (11)$$

Furthermore, the relationship between *LHV (*MJ/kg) and *HHV (*MJ/kg) of biomass can be written as follows [9].

$$HHV = LHV + 21.978 \cdot H \qquad (12)$$

where the mass fraction of hydrogen in biomass is represented by H.

2.5 Energy and exergy efficiencies

Normally, to evaluate performance of conventional gasification system, cold gas efficiency (*CGE)* was used, which was also adopted in this study for the evaluation of both conventional and CO2-enhanced gasification of biomass. The *CGE* refers to the fraction of energy stored in the biomass feed that is converted into energy of the produced syngas, which is calculated as follows:

$$\eta_{CGE} = \frac{m_{syn} \times LHV_{syn}}{m_{biomass} \times LHV_{biomass}} \tag{13}$$

A new index, gasification system efficiency (*GSE*), was also used in this study to better evaluate non-conventional gasification processes, which is determined using following equation [10]:

$$GSE = \frac{M_{syngas} LHV_{syngas} + Q_4}{M_{biomass} LHV_{biomass} + Q_1 + Q_2 + Q_3} \tag{14}$$

where Q_1, Q_2, Q_3 are the energy consumption for steam generation, CO_2 production and gasification process (kJ/h), respectively, whereas Q_4 is the thermal energy content in syngas (kJ/h).

Carbon conversion efficiency (*CCE*) can be expressed as follows:

$$\eta_{CCE} = \frac{V_{gas} \times 1000\left[CH_4\% + CO\% + CO_2\%\right] \times 12/22.4}{W\left(1 - X_{ash}\right) \times C\%} \times 100 \tag{15}$$

where $CH_4\%$, $CO\%$, $CO_2\%$ (vol%) are the gas concentration and V_{gas} (Nm^3/h) is the flow rate of dry product gas. W, X_{ash} and C% represent the flow rate of dry biomass (g/h), the ash percentage in the feed and the amount of carbon in the biomass, respectively.

The exergy efficiency of gasification system can therefore be calculated by Eq. (16):

$$\eta_{ex}^{Gasifier} = \frac{\dot{Ex}\_gas}{\dot{Ex}\_biomass + \dot{Ex}\_agent + \dot{Ex}\_heat} \tag{16}$$

2.6 Environmental assessment

Environmental analysis was performed to compare the two scenarios: conventional gasification (scenario 1) and CO_2-enhanced gasification (scenario 2). Some of the input data for environmental analysis were extracted from Aspen Plus^{TM}. A comparison between these two scenarios showed that using CO_2 as the gasifying agent had significant influence on energy and exergy efficiency. 1 Nm^3 of syngas produced through conventional and CO_2-enhanced gasification of rice straw was chosen as the functional unit in this present work. The scope of the study encompassed three stages: (1) collection of biomass for gasification system, (2) production of syngas from the gasifier and (3) recovery of heat from syngas. In terms of system boundary, it covered biomass as feedstock, supply of gasification agents, the energy requirement of all gasification units, heat recovery, CO_2 utilization and syngas production. The CO_2 and CH_4 gases were considered as the main greenhouse gases (GHG) for the assessment of environmental impact.

The environmental impact assessment was undertaken using the ReCiPe 2008 v.1.09 method embedded in SimaPro 8.0.2 software. There are eighteen categories of impacts being considered for the midpoint level [45], such as, human toxicity, marine ecotoxicity, fossil fuel depletion, terrestrial acidification etc. The further transformation and accumulation of most of the midpoints are categorized at the endpoint levels, which are as follows:

(a) damage to human health;

(b) damage to the diversity of ecosystem ; and,

(c) damage to resource availability.

3 Results and discussion

3.1 Effect of CO_2 addition and gasification temperature on syngas composition

The comparison of using air and steam as gasifying agent is shown in Table 2, which is used as benchmark for CO_2-enhanced gasification. It is evident that the use of steam as the gasifying agent with external heat input to the gasification system demonstrated better gasification performance than the use of air as the gasifying agent, which is consistent with what was reported by other researchers [8, 9].

Table 2 shows the composition of H_2, CO, CO_2 and CH_4 at various CO_2/Biomass ratios when temperature, pressure and steam/Biomass ratio were kept constant. Syngas composition under CO_2-enhanced gasification (represented by CO_2) is presented together with that of conventional gasification (represented by Con) under the same operating conditions, i.e. T = 900 °C, P = 1 atm and steam/Biomass mass ratio = 0.3.

Regardless of the level of temperature, pressure and steam/Biomass ratio, when CO_2 is added, the percentage of H_2 and CH_4 decreases whilst the percentage of CO increases. Therefore, H_2/CO ratio in syngas decreases. The enhancement of CO production with the increase of CO_2 concentration is attributed to the RBD and WGS reactions. The amount of methane in syngas decreases as H_2 and CO are formed via the reaction between steam and methane. The RBD reaction also favours the formation of more CO_2, which competes with methane formation reaction. As most of the gasification reactions are endothermic, the product gas composition is sensitive to changes in temperature, which is a crucial parameter for biomass gasification. The impact of temperature on syngas composition for both conventional and CO_2-enhanced gasification is shown in Table 3.

For both conventional and CO_2-enhanced gasification, H_2 concentration increases sharply when gasification temperature increases, whilst CO_2 concentration shows a reversed trend. The concentration of CO increases considerably as the temperature rises and reaches the maximum at around 900 °C for both cases. The concentration of CH_4 decreased steadily within the temperature investigated in this study. When temperature is in the range of 500 °C to 600 °C, endothermic char gasification and steam-reforming reactions are very slow so that the pyrolysis of rice straw plays a more significant role.

Researchers have found that CH_4 in syngas are mainly a product of pyrolysis [38, 40, 46]. With the increases of gasification temperature, the endothermic reactions are enhanced based on Le Chatelier's principle. The endothermic reactions (2), (6) and (7) contributed to the increase of H_2 while the CO formation increases because of the enhanced reactions (1) and (2) (at higher temperature). Meanwhile, CO is generated via reverse WGS reaction (reaction 4). Under CO_2 gasification, the addition of CO_2 inhibits reaction (7) and favours reaction (1). It also inhibits reaction (4) from forming more CO. Therefore, more CO exists in the gas phase; hence, reaction (2) is inhibited. In steam gasification, reaction (2) is enhanced as well as WGS reaction. In addition, the strengthened endothermic MR reaction (reaction (6)) results in the decrease of CH_4 [38, 40]**.**

Figure 2 is the three-dimensional surface plot showing the effect of both temperature and CO_2/Biomass ratio on syngas yield. It is clear that syngas yield is influenced by gasification temperature as well as CO_2/Biomass ratio. Syngas ($CO+H_2$) yield increased with the increase in temperature for all CO_2/Biomass ratios, especially at lower temperatures. This might be caused by the more dominant effect of temperature on endothermic gasification reactions.

Regarding the influence of CO_2/Biomass mass ratio on syngas production, it can be seen that at 600 ºC and a CO_2/Biomass mass ratio of 0.125, the yield of $CO+H_2$ was 0.69 Nm^3/kg of biomass, whilst at the same temperature but a higher CO_2/Biomass ratio of 0.875, syngas yield was 0.77 Nm^3/kg of biomass. The increase in CO_2/Biomass ratio from 0.125 to 0.875 at the 700 ºC resulted in 22.0% higher yield of $CO+H_2$, which was the highest among the temperature range investigated. However, at higher temperatures the benefits of adding more CO_2 under the same temperature became insignificant. When temperature was raised to 900 ºC, no obvious change was found in the yield of $CO+H_2$, which could be attributed to the balance between the two competing reactions, reverse Boudouard reaction and water gas shift reaction. It is therefore clear from Figure 2 that for CO_2-enhanced gasification process the influence of CO_2 addition at lower temperatures was more significant than at higher temperatures.

3.2 Energy analysis

CGE is one of the important parameters to show the performance of the gasifier. It provides the percent change of chemical energy contained in the gas yielded than that of the fuel. Figure 3 illustrates the effect of CO_2/Biomass ratio on CGE when the other parameters are kept constant.

The CGE value depends on the gas yield and the volumetric percentage of CO, CO_2, and CH_4 in the syngas. It is clear from Figure 3 that the CGE of CO_2-enhanced biomass gasification increases with CO_2/Biomass ratio. Generally, the CGE increases with CO_2 addition. This is because of the rising partial pressure of CO_2 enhances carbon conversion. Hence, higher efficiencies can be achieved by selecting a proper CO_2/Biomass ratio. Compared to conventional gasification, CGE of CO_2-enhanced gasification is higher and this phenomenon is directly related to CO_2/Biomass ratio. Since CGE does not take into account the heat input to the gasifier, it is not applicable for the evaluation of the viability of CO_2 addition as the extra energy required (mainly in the gasifier) might offset the advantage of additional syngas production. Therefore, in this study, the GSE, an indicator that considers energy input in the process [10], was adopted for the evaluation of CO_2-enhanced gasification process.

Figure 4 shows the effect of CO_2 addition on GSE. It can be seen from Figure 3 and Figure 4 that at the same operating conditions, GSE is 50% lower than the CGE. Although the addition of CO_2 resulted in the increase of syngas production, this might have significant influence on energy consumption of the entire gasification system. At lower CO_2/Biomass ratios, i.e. 0.125 and 0.25, the GSE values for conventional gasification were higher than that of CO_2-enhanced gasification. This suggests that CO_2 addition had more significant impact on energy requirement. In contrast, with the increase in CO_2/Biomass ratio, which resulted greater in syngas production, less energy was required and consequently, GSE values increased. The aforementioned results deduce that CGE cannot be used to assess the advantages of CO_2 addition. Based on previous discussion, it is clear that GSE is a better index to assess the performance of CO_2-enhanced gasification process. It is clear from Figure 4 that the addition of more CO_2 in the gasification process contributed to an improved GSE. When CO_2/Biomass ratio exceeded 0.37, the GSE of CO_2-enhanced gasification became greater than that of conventional gasification.

3.3 Exergy analysis

Figure 5 illustrates the change of syngas exergy by changing CO_2/Biomass ratio when other parameters are kept constant. Syngas exergy for both CO_2-enhanced gasification and for conventional gasification is also shown in Figure 5. For individual CO_2/Biomass ratios, the product gas showed higher chemical exergy values compared with its physical exergy ones. Although for each ratio, chemical exergy of the conventional process was lower than that of the CO_2 process, the physical exergy of the CO_2-enhanced process was higher than that of the conventional process. Overall, as it can be seen from Figure 5 that exergy of syngas increased with CO_2/Biomass ratio.

When CO_2/Biomass ratio was 0.125, the chemical exergy values were 4.85 times higher than the physical exergy value as a result of lower enthalpy values in the product gases. In contrast, the heating values were considerably high. The effect of gasification temperature on syngas exergy for both conventional and CO_2-enhanced biomass gasification is shown in Figure 6. The syngas exergy increases for both cases due to the increase in syngas yield. It can be seen that syngas exergy exhibited a maximum between 800 to 900 ^{o}C because of the high concentration of H_2 and CO_2 in syngas (as shown in Table 3). This suggests that carbon was completely consumed in the temperature range mentioned [22]. Thereafter, the maximum experiences a decrease due to the generation of gaseous CO and H_2, contributed by the reduction of physical exergy values. Above this maximum value, syngas exergy decreased, which was due to insufficient compensation between the decrease in syngas exergy and the increase in chemical exergy. By comparing conventional and CO_2-enhanced gasification, it is clear that syngas exergy was equally sensitive to temperature variation. Thus, the significant influence of gasification temperature and CO_2 addition on syngas exergy is better explained by Figure 7, which presents a three-dimensional surface plot for syngas exergy efficiency with respect to temperature and CO_2/Biomass ratio. The surface plot shows that at the same temperature, exergy efficiency increases with CO_2 addition.

On the other hand, exergy efficiency increased with temperature and reached a maximum at a temperature ranging from 800 °C to 900 °C, which could be attributed to the complete conversion of carbon. Beyond that temperature range, the efficiency decreased which was explained in previous discussion. The curve also indicates that gasification temperature has more significant impact than CO_2/Biomass ratio on syngas exergy efficiency. Therefore, Figure 7 provides an abstraction of operation window of the gasification process at different temperatures and CO_2/Biomass ratios in order to obtain an optimum process conditions. The exergetic efficiency of a system can be improved by several ways, such as adding a preheating process for the reactants, reducing the temperature gradient of the combustor, and using sample with less ash content.

3.4 Environmental analysis

In this study, LCA-based environmental analysis was carried out to compare conventional and CO_2-enhanced biomass gasification in terms of their environmental impacts. Figure 8 and Figure 9 show the environmental impacts under optimal process conditions in the mid-points and end-points, respectively.

It is apparent that CO_2-enhanced gasification produces lower environmental impacts than conventional gasification. The utilization of CO_2 is the key concern in the evaluation of environmental impacts of a process. When CO_2 was used as a gasifying agent, the gasification process showed clear advantages over conventional gasification, indicating a considerable reduction of the total environmental impact. According to Figure 8, the human toxicity and marine ecotoxicity were the most significant causes in mid-point category, the impacts of which were greater than conventional gasification, despite that the energy consumption was lower. In contrast, impact corresponds to climate change and fresh water ecotoxicity were almost identical for both conventional and CO_2-enhanced gasification.

Conventional biomass gasification showed greater environmental impact than CO_2-enhanced on the use of resources followed by human health and ecosystem as illustrated in Figure 9. This is due to the impact generated by extra energy requirement in CO_2-enhanced process was compensated by the amount of steam generated and CO_2 utilized. Consequently, CO_2-enhanced process exhibited a better environmental performance. In Figure 9, it is clear that human health experienced the highest impact for both processes whereas the resources were slightly lower than the human health. Then, the environmental impact of ecosystems was found to be the lowest, which was around 50% lower than the impacts on human health. Hence, the results represented the relative influence of each process on different impact categories.

3.5 Practical applications of CO_2-enhanced gasification

In most syngas applications, H_2/CO ratio and the amount of contaminants, particularly CO_2, are the crucial factors. It can be seen from Figure 10 that a desired H_2/CO ratio and an acceptable CO_2 percentage in syngas could be achieved using CO_2 as a gasifying agent. Consequently, WGS reactor could be avoided. Moreover, the utilization of CO_2, which is considered as a GHG, had a positive effect on the environment. The production of DME via biomass gasification can be considered as one of the potential applications for CO_2-enhanced biomass gasification (as shown in Figure 11). The diagram illustrates the production of DME production based on conventional and CO_2-enhanced gasification. It is obvious in Figure 11 that by using CO_2 as the gasifying agent in biomass gasification, the desired H_2/CO ratio and %CO_2 can be achieved. Hence, due to the avoidance of WGS unit in downstream, techno-economic aspect of the entire process could be significantly improved.

4 Conclusions

In this study, it was found that gasification performance was significantly influenced by CO_2/Biomass ratio and gasification temperature. The optimal CO_2/Biomass ratio and gasification temperature were found to be 0.25 and 900 ^oC. The result also indicated that the temperature has more significant effect on syngas yield than CO_2 addition. CGE of CO_2-enhanced gasification was higher than that of conventional gasification, and this trend was directly related to CO_2/Biomass ratio. At lower CO_2/Biomass ratios, GSE for conventional gasification was higher than that of CO_2-enhanced gasification.

The syngas exergy increased with CO_2/Biomass ratio. In the gas product, the chemical exergy values were found to be 2.05 – 4.85 times higher than that of their respective physical exergy values. For CO_2-enhanced gasification, the exergy efficiencies were more sensitive to temperature than CO_2/Biomass ratios. Regarding the environmental impacts, at mid-points impacts categories, CO_2-enhanced gasification resulted in lower environmental impacts than conventional gasification, mainly due to less human toxicity and marine ecotoxicity caused. Similar results were found for end-points impacts categories, which were attributed to the use of resource, human health and ecosystem. It is shown that CO_2-enhnaced gasification process has the potential to significantly improve the cost efficiency and minimize environmental impacts of DME production.

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Table 1: Basic properties of rice straw.

Higher heating value (MJ/kg)	16.0
Proximate analysis (wt. %)	
Moisture	8.9
Volatile matter	69.8
Fixed carbon	9.5
Ash	11.8
Ultimate analysis [a,b] (wt.%)	
C	45.1
H	6.2
O[c]	32.0
N	3.1
S	0. 6
[a]Dry basis. [b]Ash free basis. [c]By difference.	

Table 2 Effect of CO_2 addition on syngas composition Unit: mole

		H_2	CO	CO_2	CH_4
Conventional (air)		0.47	0.38	0.03	3.80E-04
Conventional (steam)		0.54	0.37	0.03	6.40E-04
CO_2	C/B= 0.12	0.50	0.38	0.04	4.00E-04
	C/B= 0.25	0.47	0.38	0.05	2.73E-04
	C/B= 0.37	0.44	0.39	0.06	1.96E-04
	C/B= 0.50	0.41	0.39	0.07	1.46E-04
	C/B= 0.62	0.39	0.39	0.09	1.12E-04
	C/B= 0.75	0.36	0.39	0.10	8.69E-05
	C/B= 0.87	0.34	0.40	0.11	6.87E-05

Table 3 Effect of gasification temperature on syngas composition (P= 1 atm, steam/Biomass= 0.3 and CO_2/Biomass=0.25)

Gas Component		H_2	CO	CO_2	CH_4
600°C	Conventional	0.39	0.09	0.16	9.70E-02
	CO_2	0.35	0.11	0.20	7.80E-02
700°C	Conventional	0.49	0.24	0.09	4.29E-02
	CO_2	0.44	0.27	0.12	3.46E-02
800°C	Conventional	0.53	0.35	0.04	1.28E-02
	CO_2	0.47	0.36	0.06	6.61E-03
900°C	Conventional	0.54	0.36	0.03	1.69E-03
	CO_2	0.47	0.38	0.05	7.41E-04
1000°C	Conventional	0.54	0.37	0.02	2.59E-04
	CO_2	0.47	0.39	0.04	1.09E-04
1100°C	Conventional	0.53	0.37	0.02	5.13E-05
	CO_2	0.46	0.39	0.04	2.11E-05

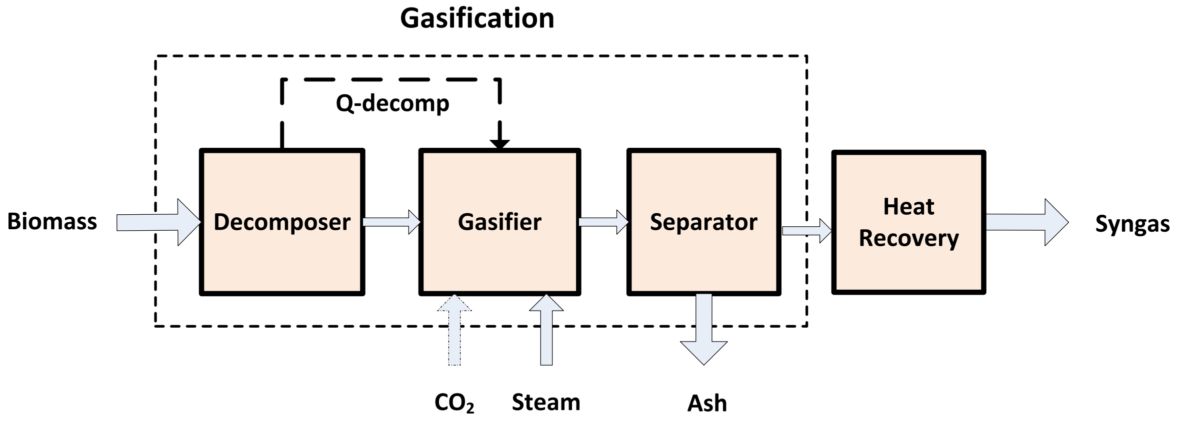

Figure 1 General schema of biomass gasification process.

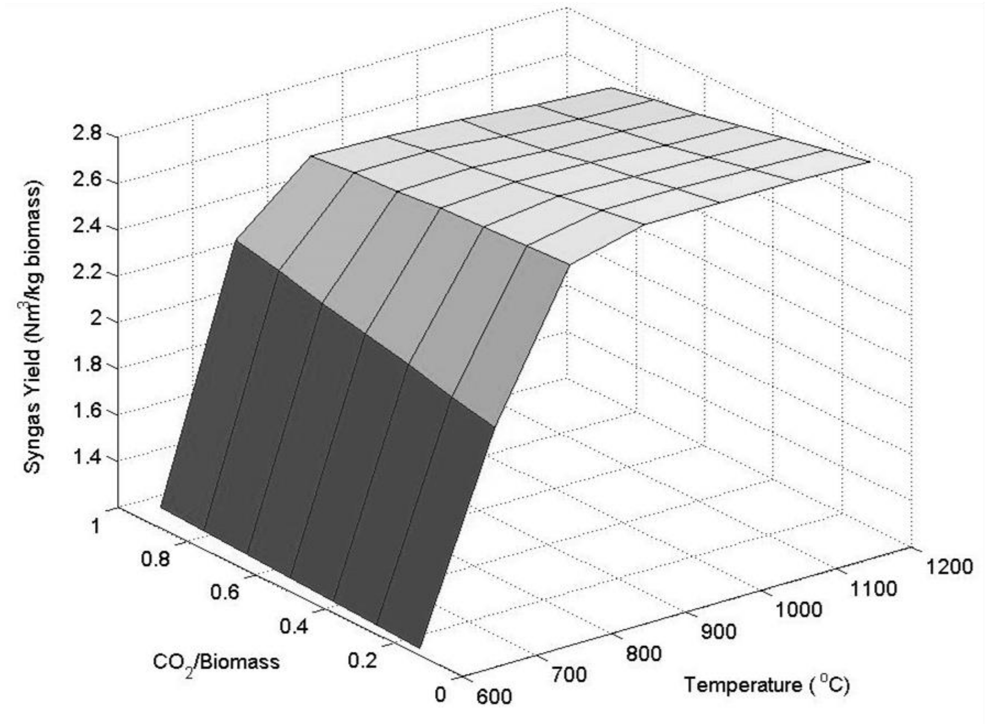

Figure 2 Syngas yield versus gasification temperature and CO_2/Biomass ratio.

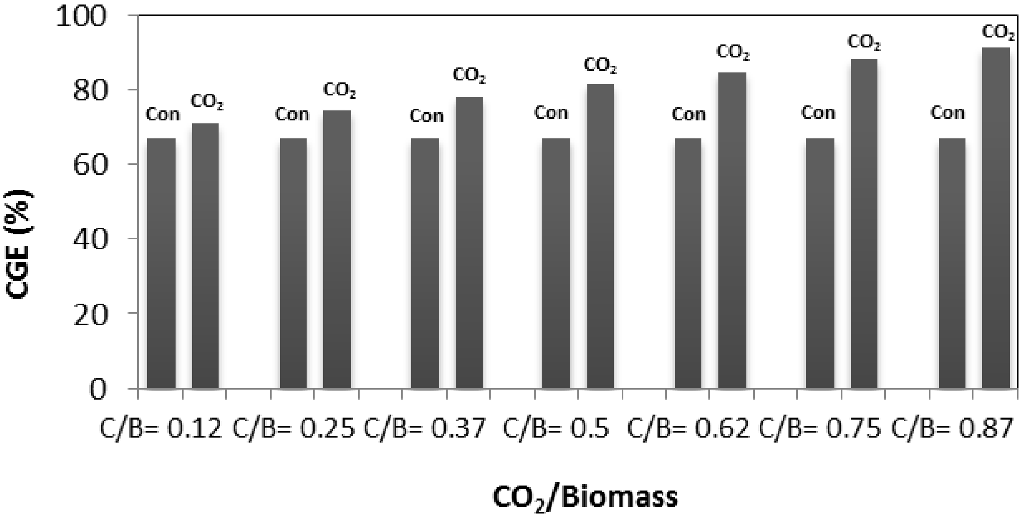

Figure 3 Effect of CO_2 addition on CGE of conventional (Con) and CO_2-enhanced (CO_2) gasification

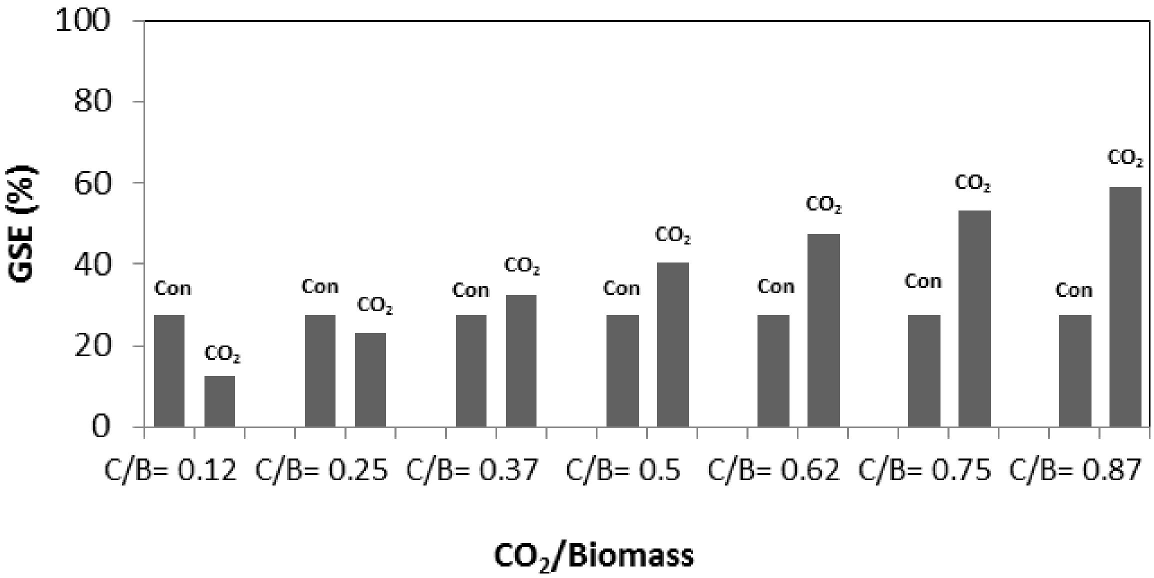

Figure 4 Effect of CO_2 addition on GSE of conventional (Con) and CO_2-enhanced (CO_2) gasification

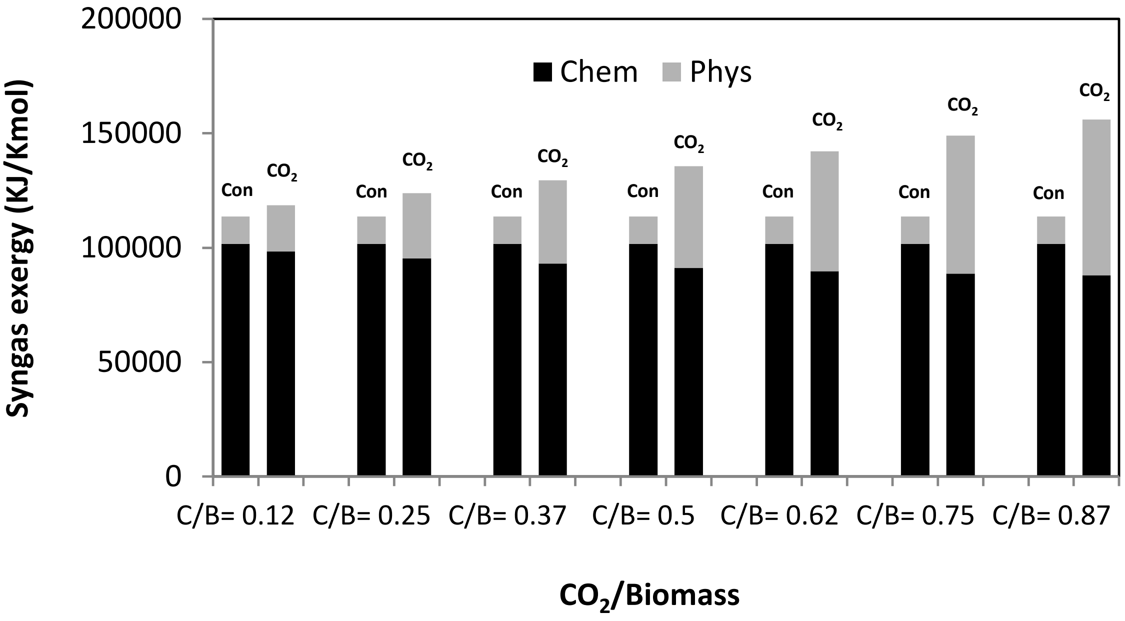

Figure 5 Effect of CO_2 addition on syngas exergy (Con: conventional, CO_2: CO_2-enhanced)

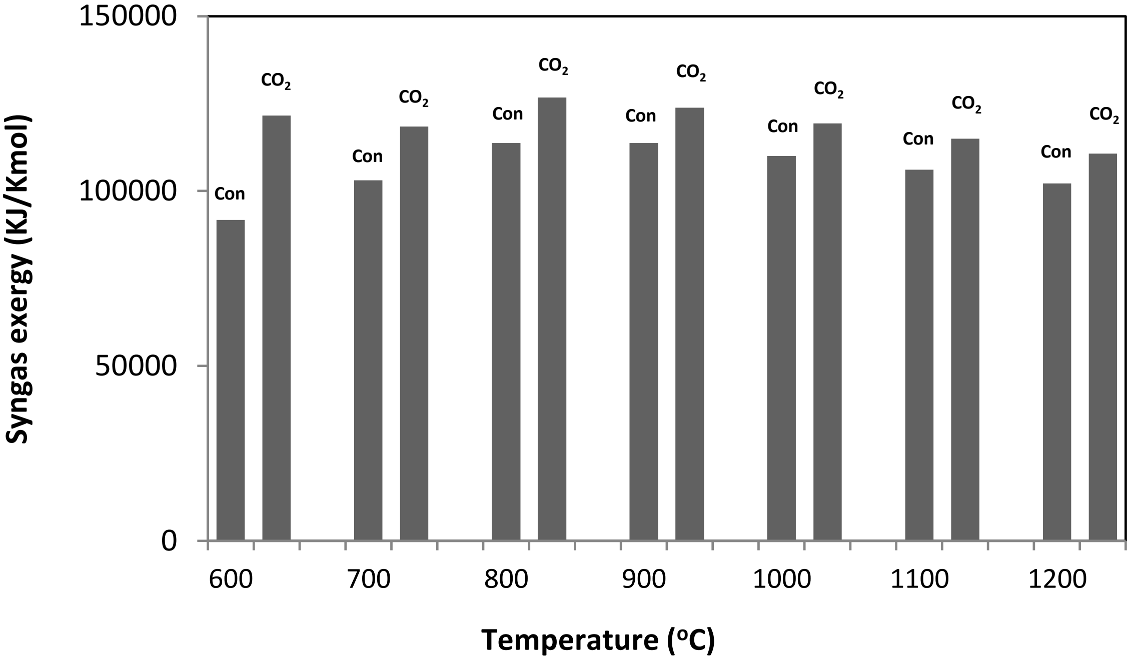

Figure 6 Effect of gasification temperature on syngas exergy (Con: conventional, CO_2: CO_2-enhanced)

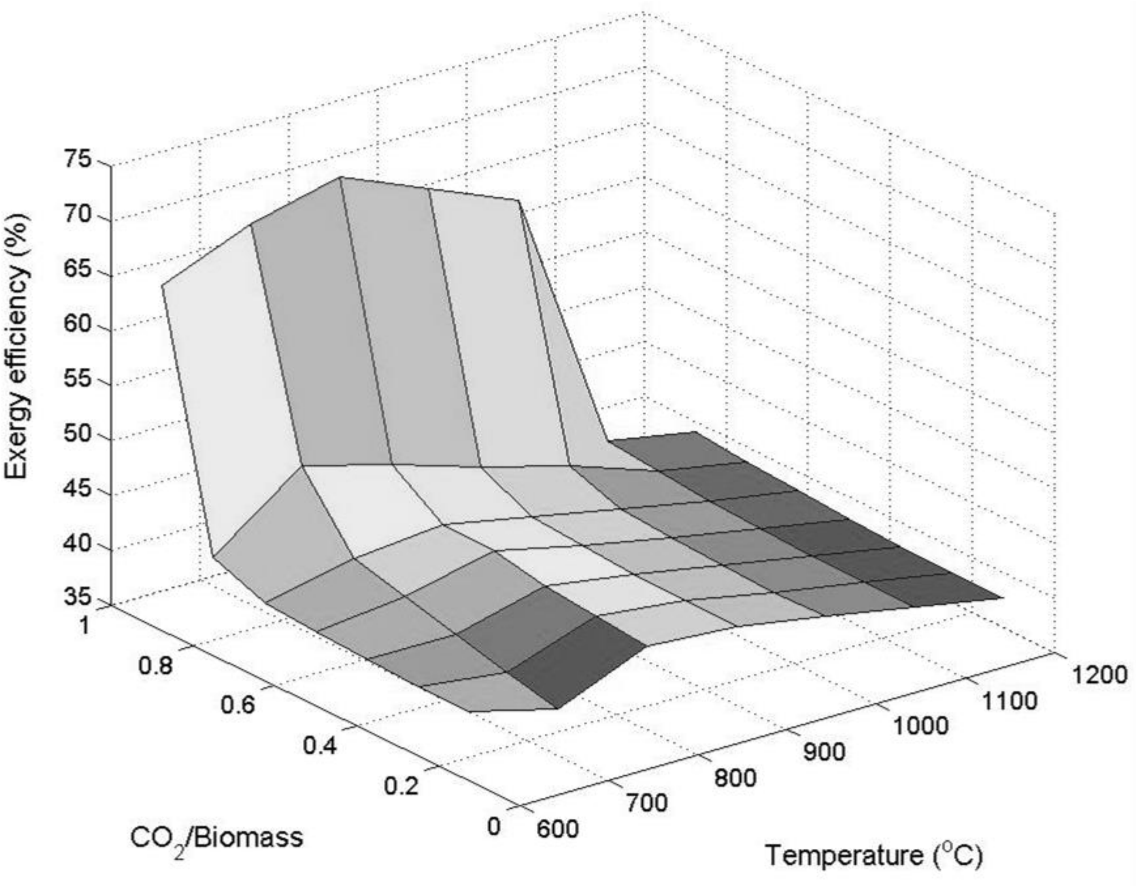

Figure 7 Exergy efficiency versus gasification temperature and CO$_2$/Biomass ratio.

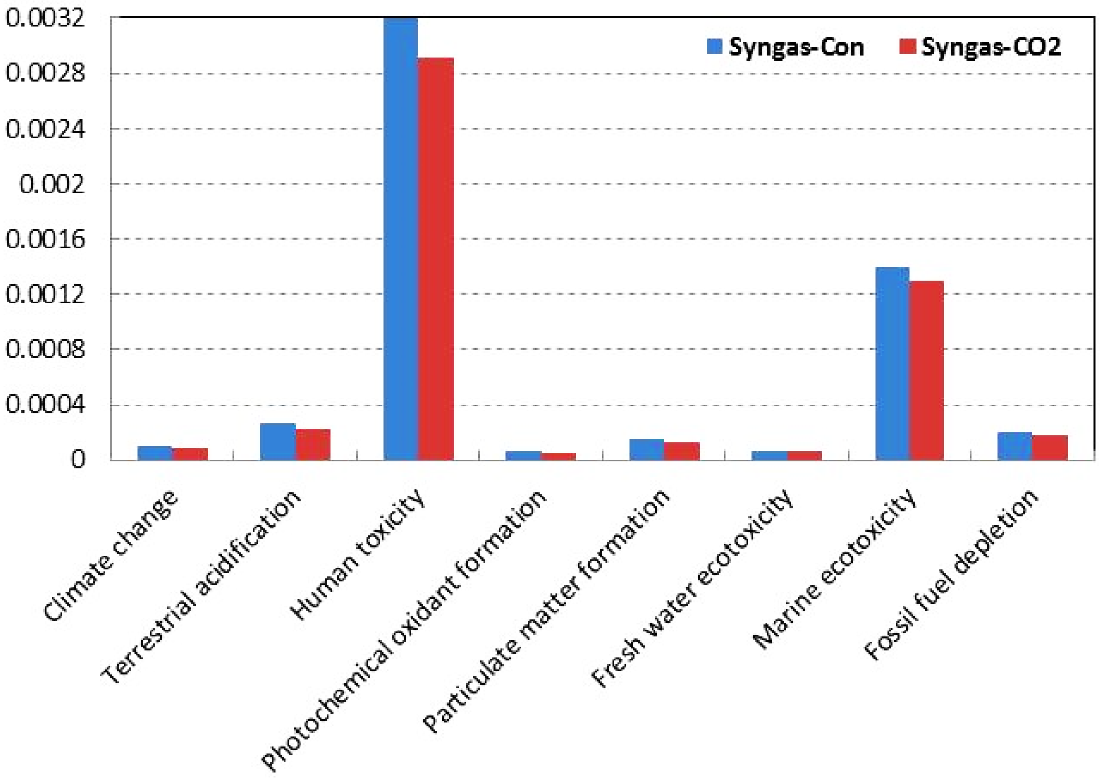

Figure 8 Environmental impact (ReCiPe) caused in different impact categories (mid-points) – conventional biomass gasification (first column) and CO_2-enhanced biomass gasification (second column).

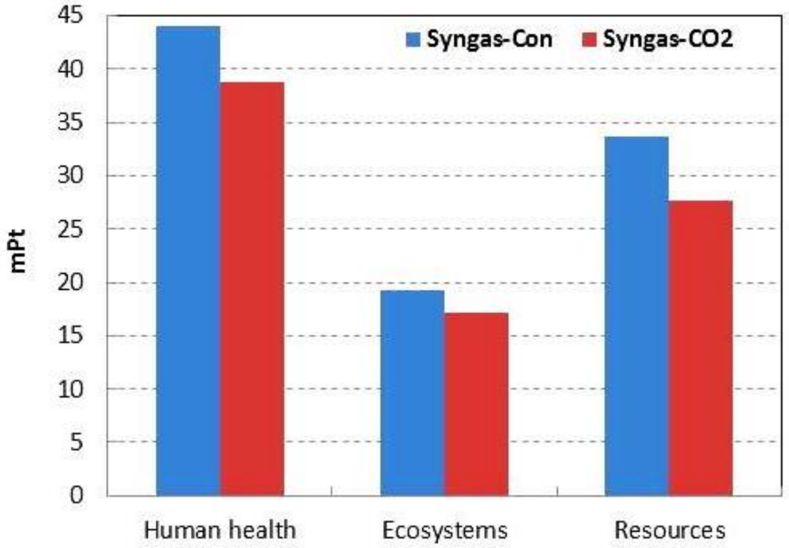

Figure 9 Environmental impact (ReCiPe) caused in the end-points - conventional biomass gasification (first column) and CO_2-enhanced biomass gasification (second column).

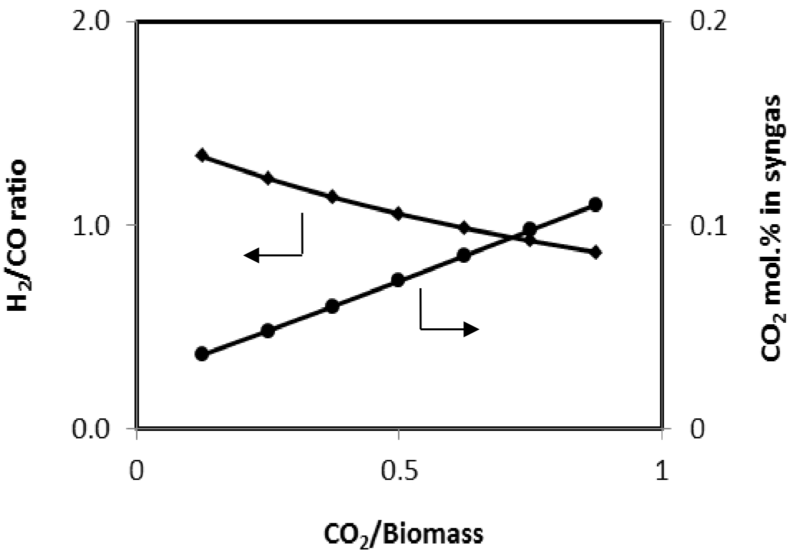

Figure 10 Effect of CO_2 addition on H_2/CO ratio and CO_2 concentration.

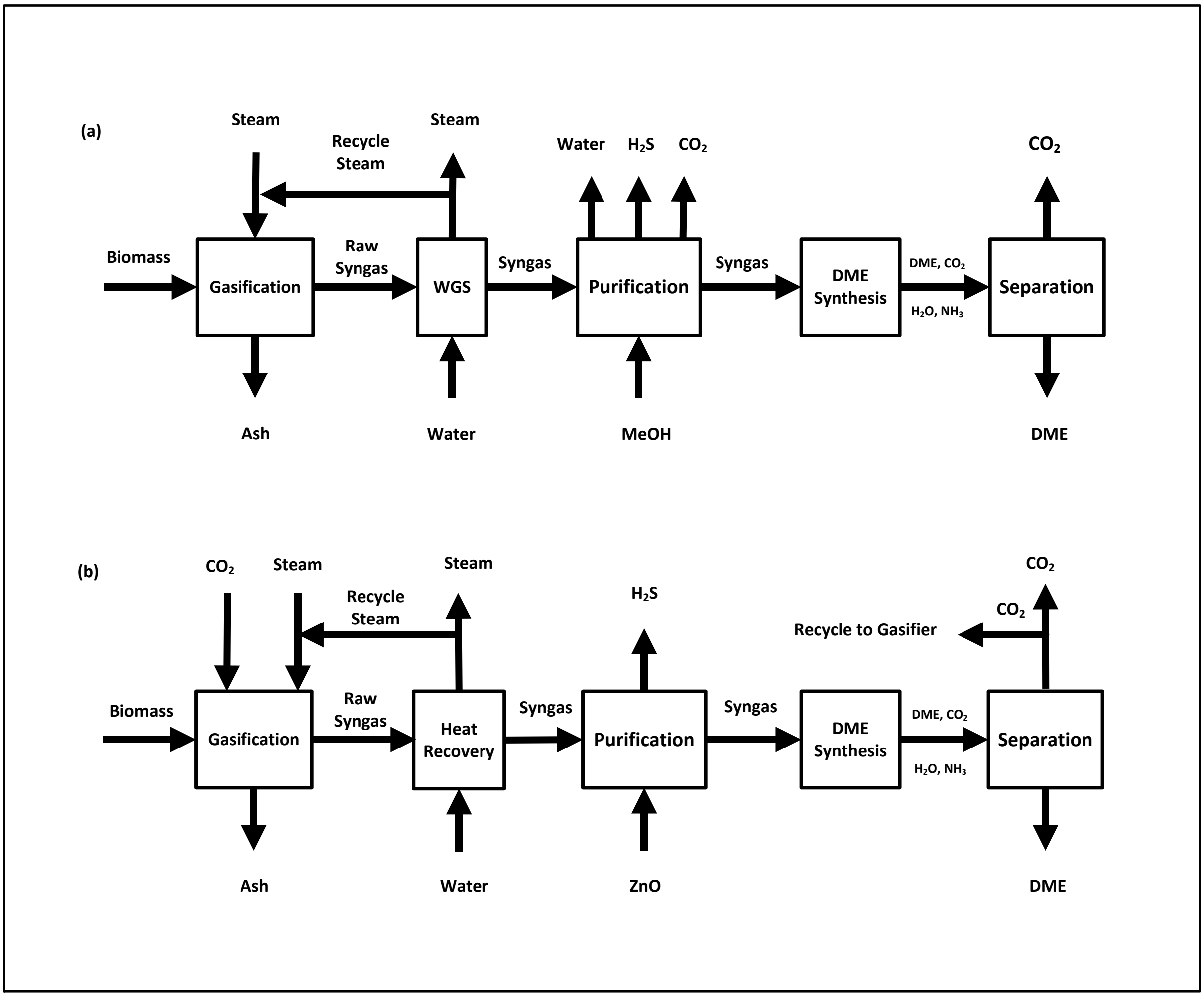

Figure 11 Diagram of single-step DME production via biomass gasification (a) conventional process [39] and (b) CO_2-enhanced process.