RESEARCH ARTICLE

SIMULATION OF O₂-BLOWN CO-GASIFICATION OF WOOD CHIP AND POTATO PEEL FOR PRODUCING SYNGAS

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HIGHLIGHTS

- Low-value biowaste including wood chip and potato peel was valorized to syngas.
- O₂-blown co-gasification of wood chip and potato peel was simulated.
- Different reaction conditions on CCE, gas composition, and LHV were studied.
- Positive interaction between wood chip and potato peel in co-gasification was found.

GRAPHICAL ABSTRACT

Simulation of the oxygen blow co-gasification of wood chip and potato peel for producing syngas
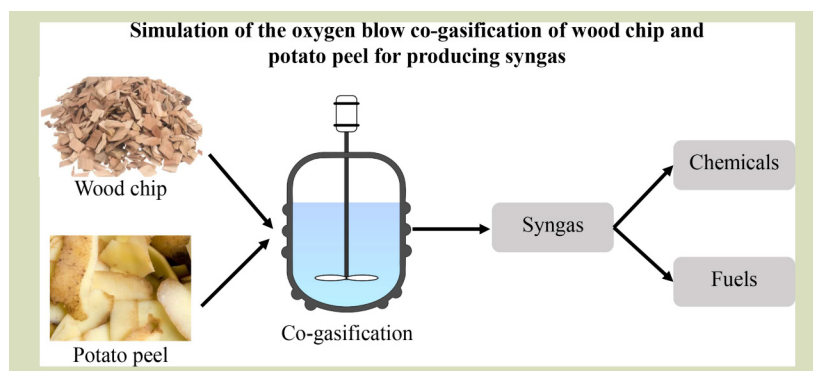
ABSTRACT

Potato is the fifth largest agricultural crop in Canada and contributes to the generation of an abundant amount of potato peel. However, disposal/recycling this peel remains a challenge due to the stringent environmental regulations. Consequently, there is a lack of an appropriate recycling and valorization methods of potato peel. Gasification is an effective technology for producing syngas and an ecofriendly waste disposal approach. Syngas is an important industrial intermediate to produce synthetic fuels and chemicals. To develop an ecofriendly and cost-effective valorization approach for potato peel, this study used a mixture of woody biomass (i.e., wood chips) and potato peel to produce syngas by co-gasification using O₂ as the gasifying agent at a constant equivalence ratio of 0.3 using Aspen Plus simulation software. The influences of gasification temperature and wood chip/potato peel weight ratio on the carbon conversion efficiency (CCE), and product gas composition (molar fraction) and lower heating value (LHV) of product gas were investigated. This simulation indicated that a positive synergistic interaction occurs between wood chips and potato peel in co-gasification process in terms of an increase in CCE by comparing the arithmetic value and real value at all simulated wood chip to potato peel weight ratios (44.9% to 85.8%, 46.5% to 76.2%, and 48.1% to 78.6% at ratios of 25:75, 50:50, and 75:25, respectively, for wood chips to potato peel). While the molar fraction of H₂ and CO decreased continuously with increase in the weight percentage of

wood chips in the wood chip-potato peel mixture from 0 wt% to 100 wt% (H_2, at 42.1 mol% to 41.4 mol%; and CO at 44.0 mol% to 40.4 mol%), accompanied by a decrease of the LHV of the product gas (10.3 to 9.78 MJ·Nm^{-3}). The study concluded that co-gasification for producing syngas is feasible and environmental-friendly option to recycle and valorize potato peel.

1   INTRODUCTION

Overexploitation of fossil fuels like coal, crude oil and natural gas, and massive emissions of greenhouse gas (GHG) have driven the government and research community to use renewable biomass and organic waste as feedstocks to produce fuels and chemicals. As outlined in the United Nations Framework Convention on Climate Change, nations worldwide have set an ambitious goal for reducing carbon and GHG emissions. For example, Canada will cut the emission by 40% to 45% below 2005 level by 2030. In recent years, the tremendous amount of attention has been given to agricultural industry and its role in the transformation to a decarbonized and sustainable global economy[1]. In terms of global emissions from the economic sectors, the emission from agriculture, forestry and other land use ranked second (only after heat and power generation) and are responsible for 24% of total emissions, as advised by Intergovernmental Panel on Climate Change in 2014. To address this, one effective solution is to recycle and reuse the substantial amount of processing waste from agricultural industries as energy sources like H_2, biogas, bioethanol and biobutanol by thermochemical, chemical or biological conversion. Among these, H_2 is a clean energy source and is widely used in oil refineries, fertilizers, chemicals and steel manufacturing. Market forecasts underscore that global H_2 production will increase dramatically from 60 Mt in 2018 to 300 Mt in 2030. Presently, the majority (> 98%) of H_2 is produced from either steam methane reforming (SMR) of natural gas (represents 76% of the global H_2 production) or coal gasification (represents 22% of the global H_2 production)[2]. While these technologies result in massive amounts of CO_2 emissions, with SMR releasing about 7 kg of CO_2 per kg of H_2 produced. Thus, there is a pressing need to develop a renewable and sustainable approach to replace SMR and coal gasification for H_2 production.

Biomass gasification is a promising H_2 production technology with tremendous possibilities to reduce the consumption of fossil fuels while concurrently addressing environmental issues in long-term planning and helping to achieve a sustainable development manner[3]. Gasification is one type of thermochemical conversion where biomass is converted into syngas (a mixture of H_2 and CO, CO_2, CH_4 and other trace gases), in which a gasifying agent is often required. A simple schematic diagram illustrating biomass gasification is given in Fig. 1. The most common gasifying agents are pure O_2, air or steam, or a mixture of these. The chemical composition, yield and heating value of the gas produced, as well as the carbon conversion efficiency of the process are dependent on the reactor configuration, gasification temperature, equivalence ratio (ER), gasifying agent and feedstock characteristics[5]. With a proper downstream treatment like reforming, pressure swing adsorption and membrane technology, a high-purity H_2 can be produced.

Recently, as reported by Value Chain Management International in 2019, approximately 58% of food is either lost or wasted each year in Canada, which is responsible for emission of 56.6 Mt·yr^{-1} CO_{2eq} due to the landfills of food waste along with a loss of > 49 billion USD·yr^{-1} to the economy[6]. Specifically, potato is the fourth largest cultivated crop worldwide after rice, wheat, and maize, and its global consumption has dramatically increased from 328 Mt in 2010 to 370.43 Mt in 2019[7]. In Canada, potatoes are considered the fifth largest agriculture crop and contribute to ~1.4 billion USD
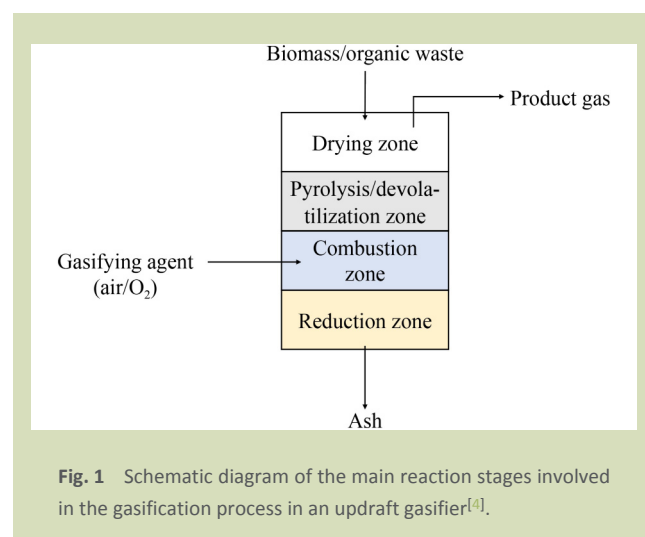

Fig. 1   Schematic diagram of the main reaction stages involved in the gasification process in an updraft gasifier[4].

in farm cash receipts and ~2 billion USD in exports of potatoes and potato products, as indicated in the Potato Market Information Review 2020–2021[8], this larger consumption of potatoes leads to a massive amount of potato peel as industrial processing waste, and its disposal/recycling remains a challenge because of the stringent regulatory environment. It has been estimated that an amount of 70–140 kt·yr^{-1} of potato peel is generated worldwide, and the most common management strategies are: (1) disposal in landfills, which contributes to environmental problems, and (2) use as animal feed with minimal added value to the production chain. To address this global challenge, the use of potato peel as a valuable resource to produce value-added bioproducts has considerable potential[9]. Thus, several studies have investigated the feasibility for recovering phenolics compounds from potato peel by organic solvent extraction[10,11] or natural deep eutectic solvent[12] and glycoalkaloids from potato peel using electro-membrane extraction method[13]. In addition, the valorization of potato peel into bioenergy and biofuels might be another productive area of research due to the merits of thermochemical conversion including (1) fast reaction rate, (2) the abilities for processing of various types of feedstocks, and (3) the potential for producing other valuable bioproducts like biochar produced from gasification.

Unlike gasification, co-gasification uses more than one feedstock in the process, which can have positive effects on H_2 production and heating value[14]. Raj et al.[15] studied the co-gasification of hard coke and mahua wood, and Lestander et al.[16] gasified a mixture of stem wood, bark, branches and needles of spruces for producing syngas. Co-gasification uses the synergistic effects among various feedstocks to produce high-quality syngas with improved process efficiency. Apart from biomass and organic waste, plastics have also been co-processed in co-gasification for H_2 and syngas production. Buentello-Montoya et al.[17] co-gasified plastic mixture (including polypropylene and polyethylene terephthalate) and straw, and the results indicated that the gas heating value increased with increasing amount of plastic but an increase in the tar content was observed. Li et al.[18] co-gasified polyethylene and pinewood under CO_2 atmosphere, in which a positive synergistic effect between polyethylene and pinewood was found with respect to energy yield. In addition to co-gasification of biomass with plastics, a mixture of coal and plastics has been investigated[19–21]. In the real application scenario, it would be interesting to see how the replacement of woody biomass with a novel biomass waste stream, such as, potato peel, would affect the chemistry and the product of the gasification process. However, there are few reports on the synergistic interaction between potato peel and other types of

biowaste during a co-gasification process to produce syngas. Therefore, in this work co-gasification of wood chips and potato peel was simulated using Aspen Plus simulation software (Version 11, Lakehead University, Ontario, Canada), and the influences of gasification temperature and ER on the carbon conversion and product gas composition and heating value. Overall, this present study not only provides an ecofriendly solution to treat a large quantities of food waste but also offers an alternative technology for production of syngas and H_2.

2   PROCESS DESCRIPTION

2.1   Feedstock characteristics

This simulation study developed a wood chip-potato peel co-gasification model for the production of syngas using Aspen Plus. Both wood chips and potato peel were simulated as the non-standard component in Aspen Plus. Non-standard component in Aspen Plus is not pure chemical species like coal and biomass. HCOALGEN and DCOALIGT models were selected to calculate the enthalpy and density of wood chips and potato peel in the simulation. The results of proximate and ultimate analyses of wood chips and potato peel are given in Table 1, which summarizes the published data[22–25]. The higher heating value of wood chips and potato peel is 17.8 and 17.4 MJ·kg^{-1}. Table 2 summarizes all components used in this simulation study.

Table 1   Results of proximate and ultimate analysis of wood chips and potato peels used in the Aspen Plus simulation

Properties	Wood chips	Potato peel
Proximate analysis (wt%)		
Moisture	21.7	8.31
Fixed carbon (db)	14.3	16.6
Volatile matter (db)	60.9	66.5
Ash (db)	3.9	8.6
Ultimate analysis (wt%) (db)		
C	46.5	43.9
H	5.8	5.8
N	0.2	3.5
Cl	0	0
S	0.1	0
O	43.5	46.8

Note: db, dry basis.

Table 2   Components used in the Aspen Plus simulation

Type	Component
Standard	H_2, CH_4, CO, CO_2, O_2, N_2, H_2O
Non-standard	Ash, potato peel
Solid	C (graphite), S

2.2   Methodology and process description

The gasification and co-gasification models were developed based on the mass, chemical and energy balance using Aspen Plus. Overall, the gasification and co-gasification processes were modeled in three main stages. (1) Moisture content of the feedstock was reduced before feeding into the reactor (RStoic module). (2) The pre-dried feedstock was decomposed in a pyrolysis/devolatilization reactor to volatile matter, hot char and ash (RYield module). (3) Combustion and reduction of volatile matter and hot char obtained from the second stage occurred to produce gaseous products by minimizing Gibbs free energy (RGibbs module).

Initially, the gasification of individual feedstock (wood chips and potato peel) was developed in the Aspen Plus and then was extended to co-gasification of wood chips and potato peel at different wood chip/potato peel weight ratios. The process for both gasification and co-gasification was modeled by a kinetic-free model under a steady-state isothermal condition. For the base method used in this simulation work, the Peng-Robinson equation of state was used, as in previous Aspen Plus simulation work regarding high-temperature gasification and co-gasification processes[4,26]. The gasification often conducts at a temperature below the melting temperature of ash to prevent ash sintering. It has been suggested that ash sintering is one of the main technical challenges aside from tar formation in the gasification process[27]. Ash sintering causes deposition on the surface of various equipment, which not only leads to a reduction in the heat transfer but also lowers the stability of the entire process[27]. Consequently, in this study, the temperature used in the gasifier (combustion and reduction zones) ranged from 500–1000 °C[4]. In this developed model, the assumptions were shown below and all assumptions made i were based on several previous studies[28–30] and were: (1) feedstock feed rate (mass flow rate) for both gasification and co-gasification were constant at 2 t·h^{-1}; (2) inlet of feedstock was 25 °C and 100 kPa; (3) pyrolysis/devolatilization stage of dried feedstock instantaneous and volatile matter consisted primarily of H_2, CO, CO_2, CH_4 and H_2O; (4) no tar was formed in both gasification and co-gasification processes; (5) no pressure drop and no heat loss were considered in this simulation; (6) all

considered components were in chemical equilibrium; (7) ash was molded as an inert solid and did not participate in the reaction; and (8) char was solely composed of carbon and underwent a complete conversion.

The process performance of both gasification of either wood chips or potato peel, and co-gasification of wood chips and potato peel, was evaluated based on the carbon conversion efficiency (CCE). CCE is defined as the ratio of the total moles of C in the C-containing gases (CO, CO_2 and CH_4) to the moles of C in the biomass (ash- and moisture-free basis)[31].

Lower heating value (LHV) of product gas is another indicator of the gasification performance, and the following Eq. (1) was used to calculate.

$$LHV_{syngas} = (10.79H_2 + 12.63CO + 39.82CH_4)/100 \quad (1)$$

where H_2, CO and CH_4 are the molar fraction in the product gas, and their heats of combustion are given in MJ·Nm^{-3}. This equation is according to the heat of combustion date and the assumption that the behavior of the gaseous species obeys the ideal gas law.

ER was defined as the ratio between the oxygen content in the oxidant supply and that required for achieving complete stoichiometric combustion. For the large-scale commercial plant, ER ranged between 0.25 to 0.35 to maximize char conversion[23], and a range of 0.2–0.3 of ER might be needed for achieving a high yield of product gas[32]. In a previous study on O_2-blown co-gasification treatment, it was observed that an increase in ER above 0.3 would lead to a decrease in the concentrations of H_2 and CO in the product gas[33]. This might be due to the oxidation of CO and H_2. Consequently, in this study, a fixed ER of 0.3 was selected for co-gasifying wood chips and potato peel.

The detailed schematic layouts of the Aspen Plus simulation of the gasification of single feedstock and co-gasification of two feedstocks are given in Fig. 2 and Fig. 3, respectively. For the gasification of single feedstock or the co-gasification of feedstock mixture, the biomass was initially dried to remove the moisture content, and the dried biomass and moisture were separated. The pre-dried biomass was then fed into the RYield reactor to decompose non-standard components (wood chips and potato peel) into standard components. In the RYield reactor, the yield distribution was defined using the ultimate analysis of the feedstock and based on the mass balance. Following this, ash was separated from the pyrolysis vapor using a separator. This pyrolysis vapor was then loaded into the RGibbs reactor module with restricted chemical equilibrium to
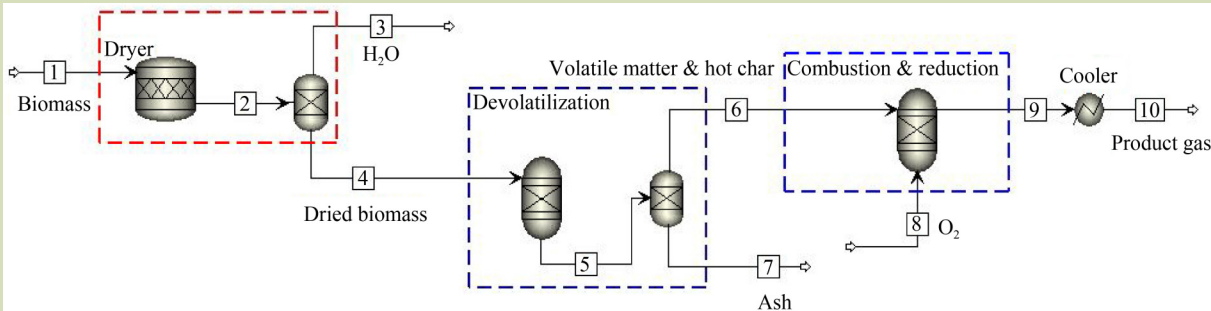
Fig. 2 The Aspen Plus simulation flow chart for gasification of single feedstock.
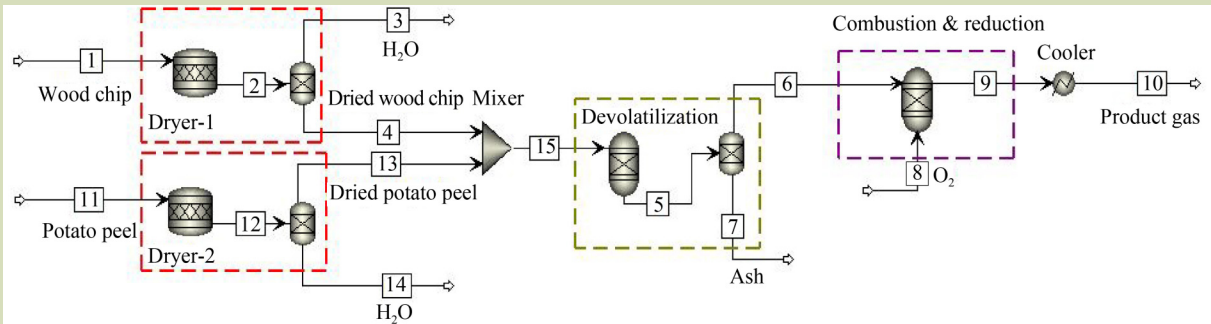

Fig. 3 The Aspen Plus simulation flowsheet for co-gasification of the mixture of wood chips and potato peel.

undergo combustion and reduction reactions where O_2 was supplied as the gasifying agent. Although the use of pure O_2 as the gasifying agent leads to an increase in the operating cost owing to the high energy demand for O_2 production, O_2 could produce the low-tar product gas in the gasification process[34]. The stream 9 (Fig. 2) was then cooled to 25 °C to yield the final product gas. The description of each block used in Fig. 2 and Fig. 3 is given in Table 3.

When comparing this simulated models with real gasification experiments, some differences must be considered. In this simulated model, biomass was pre-dried and the dried biomass is then charged into the gasifier, which is a common practice in gasification simulation work[35,36]. Similarly, in the real gasification experimental work, the biomass still needs to be pre-dried, and the moisture content of biomass needs to be reduced to less than 15 wt% to 20 wt%. High water containing

Table 3   Function of each block used in this Aspen Plus simulation

Block ID	Aspen modules	Function
Dryer step	RStoic	To remove moisture content from biomass at 100 °C and 100 kPa
	Sep	To separate moisture content and dried biomass
Mixer	Mixer	To mix dried potato peel and dried wood chips, which is only needed for the co-gasification simulation
Devolatilization	RYield	To convert non-standard components into standard ones based on the mass balance, with at 500 °C and 100 kPa
	Sep	To separate ash from volatile matter, which will further go to RGibbs reactor module. Ash is an inert material and will not participate in the chemical reactions
Combustion and reduction	RGibbs	To gasify a single feedstock and co-gasify a feedstock mixture at 500–1000 °C and 100 kPa. Pure O_2 is used as the gasifying agent
Cooler	Heater	To cool the gas produced to 25 °C

feedstock will need more energy to be consumed in the gasification, since drying is considered the first stage of a gasifying process (biomass drying, pyrolysis, oxidation and reduction) and the heat required in the drying stage is proportional to the content of moisture fraction of feedstock[37]. To facilitate the simulation, in this work, a separator was modeled after the dryer to separate moisture completely from dried biomass, followed by dried biomass went through devolatilization, combustion and reduction in the following reactors.

3   RESULTS AND DISCUSSION

Initially, the gasification of individual feedstock (wood chips and potato peel) was simulated at 500–1000 °C (combustion and reduction zone) and a constant ER of 0.3. Effect of temperature on product gas composition (molar fraction), LHV and CCE was evaluated. In the following co-gasification process, the co-gasification of the mixture of wood chips and potato peel was simulated at the temperature at combustion-reduction step was simulated at 500–1000 °C and the wood chip to potato peel weight ratio of 25:75, 50:50, and 75:25. The results were obtained from the sensitivity analysis in Aspen Plus regarding the molar fraction of H_2, CO, CO_2, and CH_4 at varying temperatures, along with the values of LHV and CCE.

3.1   Gasification of individual feedstock

Temperature is a critical reaction parameter in both gasification and co-gasification processes since it substantively affects all the endothermic and exothermic reactions involved in the treatment. As shown in Fig. 4, for both wood chips and potato peel, the molar fraction of H_2 and CO increased with increasing temperature, which is opposite to the trend of the molar fraction of CH_4 and CO_2 at different temperatures.

These results consistent with a simulation study conducted by Gu et al.[38] on co-gasification of the mixture of algae and plastic waste and another study on the simulation of syngas production by gasification of rice straw in which air was simulated as the gasifying agent. Thermodynamically speaking, H_2 production is favorable at higher temperatures, which can be indicated by the reactions $CH_4 + H_2O \leftrightharpoons CO + 3H_2$, $\Delta H = 206$ kJ·mol^{-1} (R1), and $C + H_2O \leftrightharpoons H_2 + CO$, $\Delta H = 131$ kJ·mol^{-1} (R2). Similarly, CO formation favors at higher temperatures, which can be explained by the Boudouard reaction $C + CO_2 \leftrightharpoons 2CO$, $\Delta H = 172$ kJ·mol^{-1} (R3). Clearly, according to Le Chatelier's principle, R1, R2 and R3 reactions are enhanced at higher temperatures, which leads to increased production of syngas. When temperature increases, a decrease in CO_2 molar fraction was observed, which could be due to the reaction $CO + H_2O \leftrightharpoons CO_2 + H_2$, $\Delta H = -41$ kJ·mol^{-1}. Thus, as temperature increases, more CO_2 will be consumed to form CO. These results also showed that the molar fraction of CH_4 reduced with increasing temperatures. This could be explained by the endothermic nature of R1 reaction (steam methane reforming). As suggested by Ramzan et al.[4], CH_4 formation is more sensitive to the change in temperature compared to other gaseous products. Typically, CH_4 production is favorable at temperatures lower than 400 °C since CH_4 and unburnt carbon will still be present in the syngas, but these will be converted to H_2 and CO at higher temperatures. Figure 5 shoes that the LHV increased with increasing temperature for both gasification of either wood chips or potato peel alone. This is primarily caused by an increase in the fraction of combustible gas H_2 and CO at higher temperatures[39,40]. Additionally, as expected, the CCE was proportional to the temperature. This trend is consistent with a study on the air-blown gasification of rice husk at 720–840 °C in a circulating fluidized bed reactor[41]. In addition, when comparing wood chips and potato peel, no big difference was observed in terms of gas composition and LHV. While gasification of potato peel
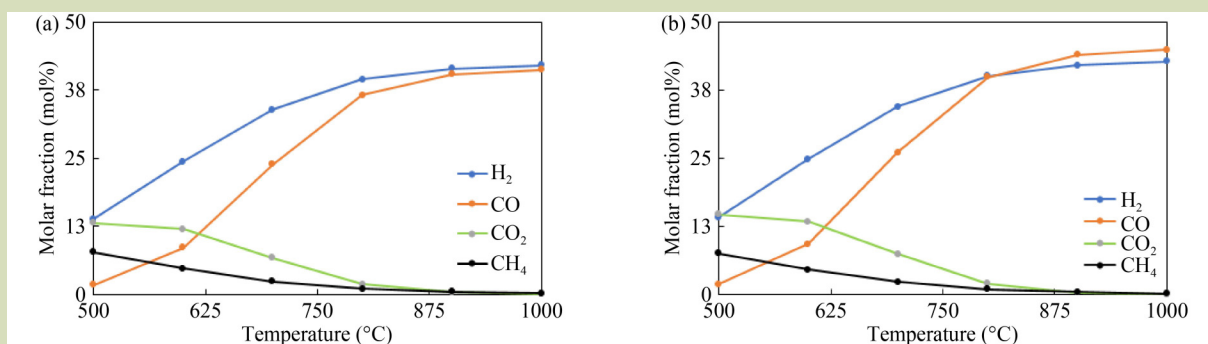

Fig. 4   Effect of temperature on molar fraction of product gas obtained from gasification of wood chips (a) and potato peel (b) at 500–1000 °C.
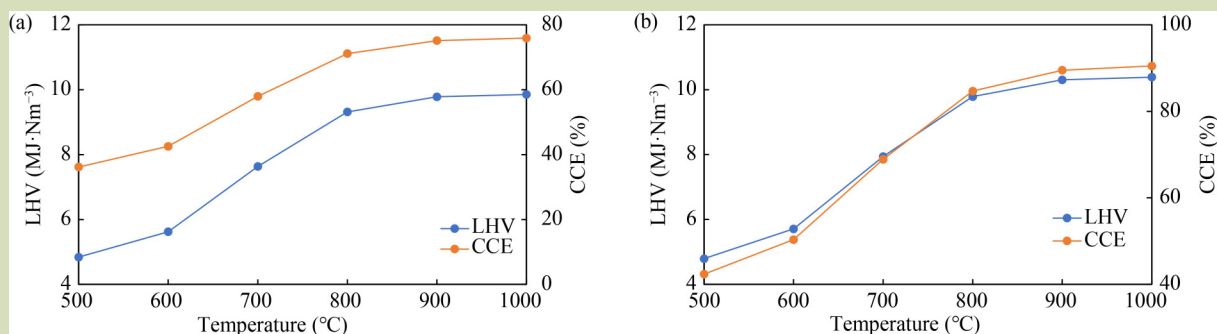
Fig. 5 Effect of temperature on LHV and CCE obtained from gasification of wood chips (a) and potato peel (b) at 500–1000 °C.

resulted in a higher value of CCE (~10%) than that of wood chips. This might be correlated to the volatile fraction of wood chips (60.9 wt%) and potato peel (66.0 wt%). In this simulation, all volatile fractions of feedstocks were assumed to be H_2, CO, CO_2, CH_4 or H_2O, and thus a greater proportion of the potato peel was decomposed to gases than for wood chips. These gas species underwent a series of reaction in the oxidation and reduction zone to form the final product gas.

3.2 Co-gasification of wood chips and potato peel

To understand the co-gasification of wood chips and potato peel for producing syngas, different wood chip to potato peel weight ratio (0:100, 25:75, 50:50, 75:25 and 100:0) were evaluated using Aspen Plus. As earlier discussed, the formation of H_2 and CO (syngas) is endothermic in nature, and thus a higher temperature is needed. Figure 4 shows that the molar fractions of CH_4 and CO_2 were almost zero for gasification of either wood chips or potato peel alone at 900 and 1000 °C. To lower energy demand, in this work, the temperature of 900 °C was selected to study the influence of wood chip and potato peel weight ratio on molar fraction and molar flow of product gas, LHV and CCE. Figure 6 shows that the highest CCE of 85.81% was obtained from co-gasification of 25 wt% of wood chips and 75 wt% of potato peel. When considering no either positive or negative synergistic effect between wood chips and potato peel, the arithmetic average value of CCE can be determined based on the weight percentage of wood chips and potato peel. The simulation results and arithmetic average value of CCE are depicted and compared in Fig. 6. Comparing these simulation results with arithmetic average value of CCE, it is speculated that the synergistic interaction occurred between wood chips and potato peel, and this interaction effect was positive. It was also found that the CCE obtained from gasification of pure potato peel (49.7%) was higher than that obtained from pure wood chips (43.3%), which implies that
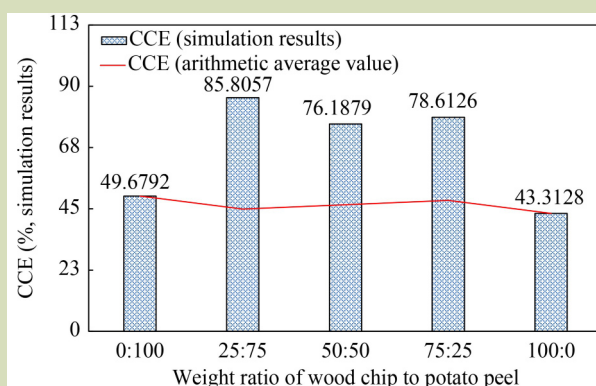

Fig. 6 CCE values from simulation results and arithmetic average at different wood chip to potato peel weight ratios.

more potato peel was decomposed and gasified than wood chips at 900 °C. Several studies have also reported the synergistic effect between different types of biomass in co-gasification treatment for H_2 and syngas production, for example, Ahmed et al.[42], Zhao et al.[43] and Huang et al.[44]. One possible reason could be the difference between wood chips and potato peel in terms of their structure and properties. Another possible reason could be the difference in the mass flow of dried biomass charging into the devolatilization/ pyrolysis stage (wood chips at 1.57 t·h⁻¹ and potato peel at 1.83 t·h⁻¹), and this is related to the higher moisture content of wood chips than that of potato peel (Table 1).

Figure 7 shows the molar fraction of H_2 gas continuously decreased with increasing the amount of wood chips in the biomass mixture. A similar trend between CO molar fraction and the weight percentage of wood chips in the biomass mixture was also observed. As expected, the reduction in the molar fraction of H_2 and CO led to decrease in LHV of the syngas when the weight percentage of wood chips increased from 0 wt% to 100 wt%.
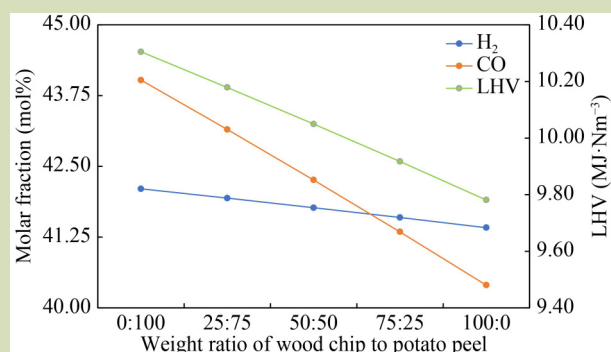
Fig. 7 Effect of wood chip to potato peel weight ratio on H_2 and CO molar fraction and LHV.

4 RECOMMENDATIONS

Due to the scope of this work, only H atoms present in the feedstocks were considered for the contribution of H_2 production. While H atoms present in the water could also contribute to the formation of H_2 in the gasification process, and this leads to a number of research work that has been conducted to use steam as the gasifying agent to enhance H_2 production in gasification[45,46]. Recently, some studies have used water as the reaction medium for gasifying[47–49] or co-gasifying[50,51] for maximizing H_2 production. In the future work, the water participation in H_2 production either by applying steam as the gasifying agent or using water as the reaction medium and performing supercritical water gasification treatment should be considered. Another recommendation that needs to be taken into consideration for the future simulation work is that the formation of tar must be

considered. In this work, to facilitate the simulation and according to some previous literature, the model developed assumed no tar formation and this led to high CCE values. To enhance this model, some recent work could provide a basis for accounting for tar production in the present model[52,53]. Also, in the future work, other types of gasifying agents especially air, steam or the mixture of these should be tested to see how they affect the co-gasification of wood chips and potato peel in terms of tar formation, and product gas yield and properties.

5 CONCLUSIONS

Using the Aspen Plus, the co-gasification of wood chips and potato peel was simulated at 500–1000 °C, different weight ratios between wood chips and potato peel (0:100, 25:75, 50:50, 75:25 and 100:0) and a constant ER value of 0.3. A sensitivity analysis was performed and the effects of temperature and wood chips to potato peel weight ratio on the molar fraction of H_2, CO, CO_2 and CH_4, LHV of product gas, and CCE were evaluated. The molar fraction of H_2 and CO increased with increasing temperature, but an opposite trend was observed for CO_2 and CH_4. LHV and CCE were observed to be proportional to the temperature. For the co-gasification, it was found that the positive synergistic interaction between wood chips and potato peel in this process by enhancing CCE value. Also, both molar fraction of syngas (H_2 and CO) and LHV gradually decreased with increasing weight percentage of wood chips in the feedstock mixture. Overall, the developed model was found to be able to predict gasifier performance under various reaction conditions, and the trends predicted were consistent with published studies.

Compliance with ethics guidelines

Yulin Hu, Kang Kang, Iker Zulbaran Alvarez, Nasim Mia, and Aadesh Rakhra declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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