Evaluation of Sugar Beet Waste in the Production of Hydrogen-Rich Gas

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Abstract- Among renewable energy sources, biomass is increasingly gaining tremendous attention due to its feedstock diversity and the way for waste management. The objective of this work is to explore the potential of the pulp, which is the waste of the sugar factory, as alternative energy for conventional energy sources through gasification technologies. Dry air was used as an oxidizing agent for the production of producer gas. Gasification experiments were carried out using different operating parameters including various temperatures (650 °C, 750 °C and 850 °C), without catalyst and with alkali catalysts (K_2CO_3, Na_2CO_3). The producer gas generated from the gasification process was identified through Micro Gas Chromatography (μ-GC) system. From the results obtained, the highest hydrogen yield is found to be 5.730 mol H_2/kg biomass in the absence of a catalyst, at 850 °C with 2 L/h dry air flow rate and 15 min. reaction time. Besides, it also revealed that K_2CO_3 is more effective than Na_2CO_3, and the maximum hydrogen yield (5.199 mol H_2/kg biomass) was achieved when K_2CO_3 used at 650 °C with 2 L/h dry air flow rate and 15 min. reaction time.

Keywords Sugar beet, waste material, gasification, hydrogen, alkali catalyst.
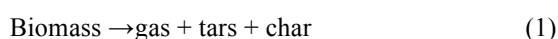
1. Introduction

Energy plays a significant role in the formation and maintenance of modern economies. The basic needs are centered on almost every aspect of human well-being, including access to agriculture, health care, employment, education, and sustainability. With the ever-growing industrialization, the need for energy is also increasing [1]. To meet this need, fossil fuels, nuclear fuels, and renewable energy sources are used. The most important reasons for the recent increase in interest in alternative renewable energy sources are limited fossil fuels, fluctuations in oil prices, threats of climate change and fossil fuels causing irreversible damage to the environment [2, 3]. Today, renewable energy technology is identified as a great engineering science that will supplant conventional fossil fuels [4].

Hydrogen occupies a prominent place in renewable energy sources because of its advantages including high energy yield, lack of harmful emissions, and producibility from diverse raw materials. In this regard, attention to hydrogen getting increased over the past years [5]. Hydrogen has an immense range of application varying from electricity generation -fuel cells, gas turbines, decentralized home energy systems, internal combustion engines and rocket fuel systems,
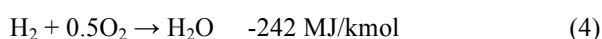
etc. - heat generation, internal combustion engines, to rocket fuel systems [6]. To add more, one of the many attention-grabbing features of hydrogen is the aforementioned ability of production from a wide range of resources such as fossil-based fuels, non-fossil-based fuels, biomass and water via various methods such as electrolysis, fuel processing and thermochemical splitting [7-9]. Among these resources and methods, hydrogen harvesting from biomass stands out with aspects like low raw material cost, low green gas emissions, and recycling of organic wastes [10].

Biomass gasification is the thermochemical conversion with solid, liquid and gas product including CH_4, H_2, CO, and CO_2 [11]. There are essentially four steps in biomass gasification, which are preheating and drying, pyrolysis, char gasification and combustion. During an ordinary gasification environment, the moisture of biomass is removed by preheating, and in pyrolysis, biomass decomposes into solids, liquids and gases. Char, tar and flue gases are formed during the pyrolysis step. Following this, resulting products proceed to the gasification step where reactions take place between char and gasifying agent to produce light valuable gases like CO_2 and H_2. The combustion reaction is crucial for the desired gas mixture since any excessive oxidant increases temperature unnecessarily and disrupts the quality of the gas by diluting it

with CO_2. In the gasification process; biomass conversion to value-added gaseous products entails a high amount of energy, therefore, the catalyst is used to let process carry out at a lower temperature for the desirable efficiency. For this purpose, NaOH, KOH, Na_2CO_3, K_2CO_3, $Ca(OH)_2$ and some transition metal (Ni, Co) catalysts are used [12, 13]. Additionally, char and tar amount that could not be reduced to a reasonable amount pose some operating and technical challenges thus requiring further treatment [14]. The foremost reactions occurring during biomass gasification can be given as follows [15, 16]:
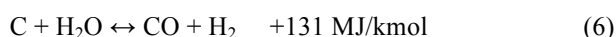
$$\text{Biomass} \rightarrow \text{gas} + \text{tars} + \text{char} \tag{1}$$

The combustion reactions

$$C + 0.5O_2 \rightarrow CO \quad \text{-111 MJ/kmol} \tag{2}$$

$$CO + 0.5O_2 \rightarrow CO_2 \quad \text{-283 MJ/kmol} \tag{3}$$

$$H_2 + 0.5O_2 \rightarrow H_2O \quad \text{-242 MJ/kmol} \tag{4}$$

The Boudouard reaction

$$C + CO_2 \rightarrow 2CO \quad \text{+172 MJ/kmol} \tag{5}$$

The water-gas reaction

$$C + H_2O \leftrightarrow CO + H_2 \quad \text{+131 MJ/kmol} \tag{6}$$

The methanation reaction

$$C + 2H_2 \leftrightarrow CH_4 \quad \text{-75 MJ/kmol} \tag{7}$$

The water-gas shift reaction

$$CO + H_2O \leftrightarrow CO_2 + H_2 \quad \text{-41 MJ/kmol} \tag{8}$$

Steam reforming reaction

$$CH_4 + H_2O \rightarrow CO + 3H_2 \quad \text{-206 MJ/kmol} \tag{9}$$
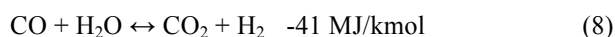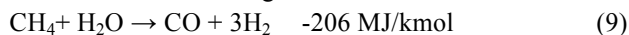
Turkey has immense potential for the production of sugar beet in the world. In spite of abundance appropriate cultivation areas around the country, the majority of sugar beet production is obtained from Central Anatolia region. Although it varies from region to region, sugar beet mainly consists of 75% water, 20% sugar and 5% pulp. Sugar beet pulp, a by-product of sugar processing industry, is rich in cellulose, hemicellulose, pectin and also encompasses a small fraction of lignin. [17,18]. It is often used as a forage source but there are ongoing studies for different utilization of sugar beet pulp [19].

A number of reports regarding gasification of various types of biomass are available in the literature, however, studies on sugar beet waste are quite scarce. Huang et al. [20, 21] concentrated on the extraction and characterization of the pectin supplied from sugar beet pulp.

Yilgin et al. [22] studied flash pyrolysis of Soma lignite (SL) (supplied by Turkish Coal Enterprises), pulp and the blend containing SL-pulp with a ratio of 50/50 (wt./wt.) to determine char, liquid and gas yield at 650 °C. It was reached that pulp supplied higher liquid yield, while SL gave higher char yield under the same condition. Besides, pulp and SL 50/50 blend gave the expected yield value.

Ziemiński et al. [23] studied methane fermentation of pre-treated sugar beet pulp using the batch anaerobic fermentation process. Maximum methane yield produced at 160 °C with the value of 502.50 L CH_4/kg sugar beet.

Bellido et al. [24] investigated acetone-butanol production from sugar beet pulp with the value of 62.3 and 80.9 g per kg sugar beet pulp, respectively.

It can be concluded that there is no detail research paper on gasification of sugar beet waste. To fill this knowledge gap, the present study aimed at examining the gasification of different type of sugar beet waste to attain high H_2 yield gas. The effect of reaction temperature, catalyst on product distribution, gas product yield, carbon conversion efficiency and heating value were investigated [25-28]. Furthermore, alkali catalyst especially K_2CO_3 is known as a good catalyst for biomass gasification [29]. In addition to this, being cheaper than metal-based (Cu/Ru) catalyst and being reactive than transition metal catalyst (Fe/Ni-based catalysts) make alkali catalyst attractive for applying in biomass gasification [30]. Consequently, taking into account all above, K_2CO_3 and Na_2CO_3 have been chosen for catalytic gasification of sugar beet waste.

2. Material and Method

2.1. Materials

Three particular waste materials of sugar beet (biomass) were used in gasification. Which are:

➢ Extracted sugar beet (Pulp)

➢ Waste of unextracted sugar beet (WUNESB)

➢ Sugar beet branch (Stalk)

Sugar beet waste sample was supplied from Eskisehir Sugar Factory which is located in the north-west of the Central Anatolia Region of Turkey. K_2CO_3, Na_2CO_3 and all reagents were supplied from Carlo Erba, and high purity dry air was supplied from a commercial company in Turkey. While all the chemicals were used without any pre-treatment, the waste materials were dried at ambient temperature before gasification.

2.2. Equipments

Updraft tubular gasification reactor was used to gasify the biomass. 316 Stainless steel gasifier's internal diameter is 10 mm and its length is 900 mm. Heat is provided by an external source that is able to raise the gasifier temperature from ambient temperature to 850 °C in a minute. Thermal insulation of gasifier is achieved by means of a cylindrical-shaped ceramic insulator. The flow rate of high purity dry air was controlled by a flow regulator prior to introducing to the reactor. The gasifier is fitted with a gas-liquid separator that allows separation of resulting gases from the liquid product. Then, the gaseous product undergoes moisture and particle trap for further cleaning before passing through a gas sampling bag. Dry air flow is gauged by the standard flow meter. Obtained producer gas analyzed using micro gas chromatograph (μ-GC) (T-3000 series) equipped with thermal conductivity detector (TCD) coupled to MS5A (molecular sieves 5 Å) and PPQ (PolarPlot Q) columns. He and Argon are

used as a carrier gas in the μ-GC whose calibration is done by using a standard gas mixture. Fig.1 provides a schematic view of the experimental setup.
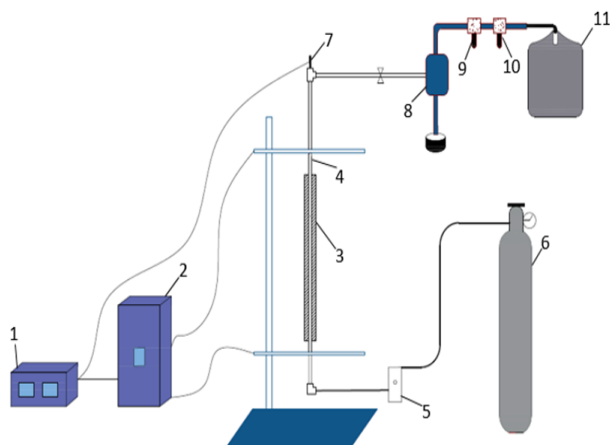

Fig. 1. Scheme of gasification system 1. Controller 2. Power supply 3. Ceramic insulator 4. Gasifier 5. Flow regulator 6. Dry air 7. Thermocouple 8. Gas-liquid separator 9. Moisture trap 10. Particle trap 11. Gas sampling bag.

2.3 Experimental procedure

Samples were air dried and milled at 8000 rpm with a rotary cutter mill prior to gasification. The elemental composition (C, H, N, O) of materials was analyzed using the (FlashSmart CHNS/O) elemental analyzer. The determination of proximate (extractives, hemicellulose, lignin, cellulose, moisture, ash) analysis of materials was done according to standard methods [31]. Stated waste materials were gasified individually and in the form of a mixture as well. For accuracy, the experiments were replicated three times with a precision of product efficiencies of around 5%.

2.3.1. Proximate analysis

Analysis of extractives: Sugar beet waste (G_0, g) was placed in a Soxhlet extractor after being dried in the oven at 105 °C to a constant weight. Using a mixture of 2:1 Benzene: Ethanol (v/v), the extraction process was carried out for 3 hours. Then, the sample was dried to a constant weight in the oven. The remaining sample was cooled down to ambient temperature in a desiccator, and then its weight was recorded (G_1, g). Eq. 10. was used for determination of the extractives percentage (W_1).

$$W_1(wt\%) = \frac{G_0 - G_1}{G_0} \times 100 \qquad (10)$$

Analysis of hemicellulose: The residue coming from the extraction was boiled for 3.5 hours in 150 mL NaOH solution (20 g/L) under the reflux. It was filtered, followed by washing with distilled water until it was free from Na^+ ions. The washed residue was dried to a constant weight, cooled down to ambient temperature in a desiccator and weighed (G_2, g). The hemicellulose proportion (W_2) was determined by using Eq. 11.

$$W_2(wt\%) = \frac{G_1 - G_2}{G_0} \times 100 \qquad (11)$$

Analysis of lignin: After extractive analysis, approximately 1 g of the sample was dried to constant weight in the oven and then weighed after cooling to room temperature in a desiccator (G_3, g). 30 mL H_2SO_4 (72%) was added carefully into the sample, and it was kept at 4 °C for 24 hours. Then 300 mL of distilled water was transferred into the mixture and it refluxed for 1 hour. After cooling, the sample was filtered, and the residue was washed with distilled water until it was free from SO_4^{-2}. The residue was dried in the oven, cooled to room temperature in a desiccator and weighed (G_4, g). The percentage of lignin (W_3) was identified by applying Eq. 12.

$$W_3(wt\%) = \frac{G_4(1 - W_1)}{G_0} \times 100 \qquad (12)$$

Determination of ash content: The crucible was heated in a muffle furnace at 600 °C for 24 h. It was then left at ambient temperature to cool down in a desiccator and its weight was recorded. After that, 10 g sample containing crucible was placed in the furnace for 24 hours at 1200 °C. After that, it was removed from muffle furnace, and measuring of weight was done after being cooled in the desiccator.

Analysis of cellulose: The percentage of cellulose (W_4) was calculated using Eq. 13.

$$W_4 = 100 - (Ash + W_1 + W_2 + W_3) \qquad (13)$$

Determination of moisture content: The measuring of moisture content of biomass samples was done by Dean-Stark Distillation unit. 10 g sample and a certain amount of saturated xylene, as a solvent, was added to a flask together. Then, the mixture was boiled until a constant volume of extracted water layer was obtained.

2.3.2. Gasification of the waste of sugar beet

In order to obtain hydrogen-rich gas product from the waste of sugar beet different reaction parameters were used such as catalyst type (K_2CO_3, Na_2CO_3) and catalyst to biomass ratios for K_2CO_3 (20, 30, 40 wt./wt.) and reaction temperature (650, 750 and 850 °C).

Gasification reactions were carried out using the updraft gasification reactor. Since the tubular reactor is able to withstand temperature up to 900 °C, the reaction took place up to 850 °C. In order to determine the influence of catalyst loading amount on gasification, 2 g of sugar beet waste and different amount of catalyst (K_2CO_3) were mixed before inserting into the reactor.

The temperature controller unit is responsible for setting the desired gasifier temperature, and about 1 minute is needed to get to the required temperature. According to authors previous work of biomass gasification, the maximum hydrogen yield was achieved at 15 min. Therefore, all experiments were performed at the reaction time of 15 min. [32]. Dry air was used with the flow rate of 2 L/h as an oxidizing agent to initiate gasification reactions. The resulting gas was taken in a gas sampling bag. Suitable reaction parameters were determined using the K_2CO_3 catalyst. Additionally, gasification products distribution (solid, liquid and gas) and the gaseous product composition were investigated depending on temperature and catalyst.

The lower heating value (LHV) of hydrogen-rich gas was calculated using Eq. 14. where CO, H_2, CH_4 and C_nH_m are the molar percentage of components of hydrogen-rich gas [33].

$$LHV(STP\ m^3) = (30.0 \times CO + 25.7 \times H_2 + 85.4 \times CH_4 + 151.3 \times C_nH_m) \times 4.2 \qquad (14)$$

Carbon conversion efficiency η_c (%) was calculated on a water and ash free basis using Eq. 15 [34].

$$\eta_c = \frac{number\ of\ mol\ of\ C\ in\ the\ gas\ phase}{number\ of\ mol\ of\ C\ in\ biomass} \times 100 \qquad (15)$$

3. Result and Discussion

3.1. Composition of waste materials of sugar beet

The composition of waste materials of sugar beet is given in Table 1. As seen from Table 1. all the waste greatly comprises hemicellulose and cellulose components despite of different percentages. WUNESB is rich in hemicellulose, whereas both pulp and stalk are rich in cellulose. Pulp possesses the highest lignin content and lignin content of WUNESB and stalk is almost the same by a small percentage. In addition, extractive content varies noticeably with the type of waste; pulp appears to have the lowest amount of extractives, whilst the highest content of extractives is found in WUNESB. Although there are no significant differences in ash content among the wastes, WUNESB has the most ash proportion.

In order to determine the effect of reaction temperature on the hydrogen yield, experiments were conducted at various temperatures (650, 750 and 850 °C) using a certain amount of sugar beet waste in absence of a catalyst and 15 min. reaction time. As demonstrated in Fig. 2. the reactor temperature was increased from 650 °C to 850 °C in 100 °C increments, hydrogen yield enhanced steadily between 650-850 °C. While temperature is 650 °C the yield was obtained 3.220 mol H_2/kg pulp. As the reaction temperature raised from 750 to 850 °C, the yield of hydrogen had a substantial increase from 4.424 to 5.730 mol H_2/kg pulp. From Fig. 2. it can be concluded that temperature is favorable for the increase of hydrogen yield. This might be attributed to the higher temperature that provides a suitable environment for endothermic reactions. Consequently, The Boudouard reaction (Eq.5), water-gas reaction (Eq.6) and steam reforming reaction (Eq.9) become predominant and are mainly responsible for hydrogen production with elevated temperature, while water-gas-shift reaction (Eq.8) is slightly exothermic and less important at the higher temperature [12].
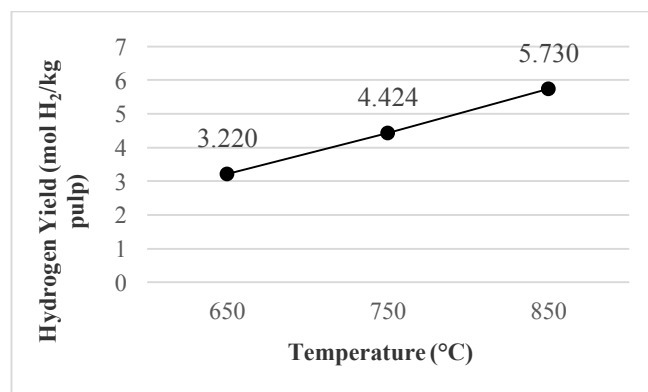
Table 1. The result of proximate and ultimate analysis of pulp, WUNESB and stalk

Proximate analysis	Pulp (wt.%)	WUNESB (wt.%)	Stalk (wt.%)
Ash	5.013	7.273	5.766
Hemicellulose	31.950	47.695	24.220
Cellulose	44.167	23.649	44.451
Lignin	8.108	5.913	5.193
Extractives*	10.690	15.170	19.650
Ultimate analysis			
C	40.509	38.171	34.380
H	5.666	5.299	4.964
N	2.083	2.692	1.845
O	51.741	53.838	58.811

* Benzene-Ethanol extractives

3.2. Gasification of waste material of sugar beet

3.2.1. Pulp

Influence of temperature: Temperature has a pivotal effect on overall biomass gasification. Based on Le Chatelier's principle, the temperature effect on producer gas depends on the thermodynamic behavior of reactions. Biomass gasification involves a large number of exothermic and endothermic reactions. Thus, temperature control is crucial to attaining a high quality of producer gas, and higher temperature favors the reactants in exothermic reactions and the products in endothermic reactions.

Fig. 2. Influence of temperature on hydrogen yield obtained from gasification of pulp (without a catalyst, 2 L/h air flow rate, 15 min. reaction time)

Gasification performance parameters such as gas yield, carbon conversion efficiency and gas LHV was analyzed under different temperature environment. From Table 2., the gas yield that can be explained as a fraction of pulp particles converted to gaseous products is increased greatly from 0.740 to 0.900 STP m^3/kg with temperature. This means higher temperature resulted in a higher conversion of pulp into gaseous products. Gas yield enhancement could be ascribed to joint impact of pyrolysis, devolatilization reactions as well as gasification reactions with increasing temperature. Meanwhile, carbon conversion improved from 84.716% to 95.061% at a specified temperature range, and this validates gas yield result because rising temperature rendered possible the release of more gaseous products (Table 2).

Table 2. Experimental result of different reactor temperature (without a catalyst, 2 L/h air flow rate, 15 min. reaction time)

Reactor temperature (°C)	650	750	850
Gas yield (STP m^3/kg biomass)	0.740	0.800	0.900
Carbon conversion efficiency (%)	84.716	89.457	95.061
Gas LHV (kJ/STP m^3)	10263	9452	10298

The temperature has a significant effect on gas product composition. H_2 and CO content in the producer gas play an influential role for being used in downstream applications. As presented in Fig. 3. CO content exhibited an upward trend with increasing temperature. It also exceeded H_2 content at all studied temperatures and reached its maximum value at 850 °C as 8.861 mol/kg pulp. Partial oxidation of char (Eq.2), Boudouard reaction (Eq.5), particularly water-gas reaction (Eq.6) were strengthened with an increasing temperature that might have made a huge contribution to CO content. Obtaining of CH_4 was accomplished through methanation reaction (Eq.7) and steam reforming reaction (Eq.9) occurring during biomass gasification. High CH_4 content was obtained when reaction already initiated at 650 °C with a value of 1.480 mol/kg pulp however, further temperature raising caused a constant trend in CH_4 content with a small decline. Therefore, a higher temperature is unfavorable for CH_4 formation. To attain a better quality of combustible gases, CO_2 content takes into account during biomass gasification, since it leads to lessening heating value and makes purification processes more challenge. In this study, the increasing temperature did not show an obvious change in CO_2 production except for the experiment conducted at 850 °C in which a slight increase was observed. Ethane-propane amount reduced from 0.401 to 0.313 mol/kg pulp while the temperature was varied from 650 to 750 °C, whereas ethane-propane content showed contrast trend with the further increase in temperature and found to be 0.542 mol/kg pulp at 850 °C. The variation of ethane-propane was emphasized since both CH_4 and ethane-propane have a greater heating value compared to other species in producer gas according to Eq. 14. Consequently, gas LHV was similarly

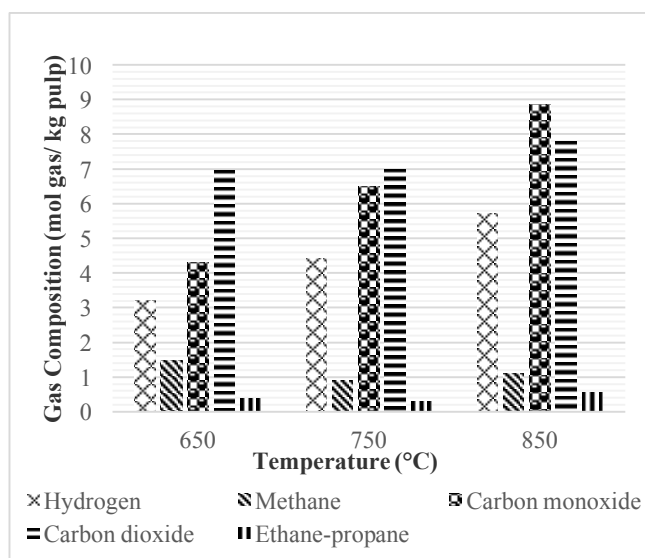decreased at 750 °C but reached a maximum value of 10298 kJ/STP m^3 at 850 °C.

Fig. 3. Influence of temperature on gaseous product composition (without a catalyst, 2 L/h air flow rate, 15 min. reaction time)

Influence of catalyst ratio: Gasification processes entail high temperatures to lower residual tar and convert biomass into a valuable gaseous product such as hydrogen. This high energy requirement undermines gasification processes to be economically viable. A lower gasification temperature is therefore desirable not merely for energy efficiency, but also for preventing operational challenges relating to high temperatures. Catalytic biomass gasification as a promising technique to enable the biomass to gasify at a lower temperature, and it promotes high conversion and high thermal efficiency [12]. Additionally, optimizing of tar removal and upgrading of syngas can be achieved through a suitable catalyst.

Unlike the non-catalytic study, the catalytic study was conducted at 650 °C due to the reasons aforementioned above. The catalyst was directly added to the feed by dry mixing. K_2CO_3 was employed as a catalyst, experiments were carried out using different catalyst ratios (20, 30, 40% wt./wt.) and results given in Fig. 4. It illustrates that the hydrogen yield initially increased rapidly until a certain value of 20 wt.% catalyst ratio with a yield of 5.199 mol H_2/kg pulp. As mentioned previously, a possible reason explaining this phenomenon is the dominance of water-gas shift reaction at lower temperature accompanied by catalyst [35]. Thereafter, hydrogen yield dropped slightly to 4.983 mol H_2/kg pulp at a catalyst ratio of 30 wt.%. Further catalyst addition appeared to have no significant change on hydrogen yield, and it maintained at the same level. According to obtained results, even though the K_2CO_3 catalyst showed inferior hydrogen yielding performance compared to the case without a catalyst at 850 °C, it is still found to be effective on hydrogen production with the ratio of 20 wt.%. Therefore, this situation met our expectations and gave the result we desired prior to experiment since using catalyst aided us in reducing energy cost and impeding operational challenges with respect to a higher temperature.
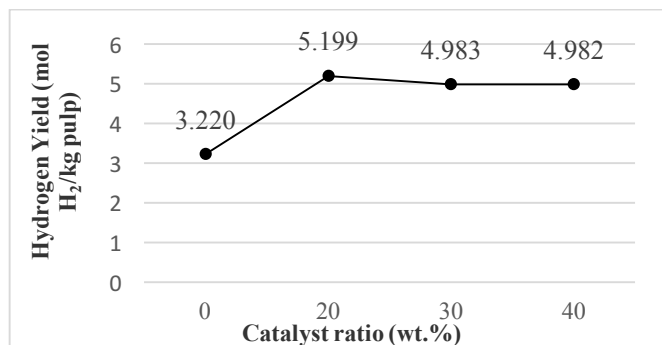
Fig. 4. Influence of catalyst (K_2CO_3) ratio on hydrogen yield obtained from gasification of pulp (650 °C, 2 L/h air flow rate, 15 min. reaction time)

To compare different catalyst activity with K_2CO_3, further experimental investigations were performed using 20 wt.% catalyst. Apart from K_2CO_3 catalyst, another alkali-based catalyst; Na_2CO_3 was used to examine different catalyst performance on the hydrogen yield at suitable conditions determined for K_2CO_3. Comparison of the activity of K_2CO_3 and Na_2CO_3 catalysts on hydrogen production in gasification of pulp given in Fig. 5.

As shown in Fig. 5, although both catalysts belong to the same group (IA of the periodic table), catalytic activities are significantly different. Clearly, the highest yield of H_2 from the pulp was achieved in the case of using the K_2CO_3. Eventually, the effectiveness of Na_2CO_3 catalyst on pulp gasification in relation to hydrogen yield was quite lower. One possible explanation of Na_2CO_3 catalyst giving lower hydrogen yield could be coke deposition on catalyst leading to catalyst deactivation. Another possible explanation is the superior catalytic activity of K alkali metal compared to others [30]. According to the literature review, various biomass was gasified using alkali catalysts, and it was also reported that K_2CO_3 has a better catalytic effect than Na_2CO_3 [35,36].
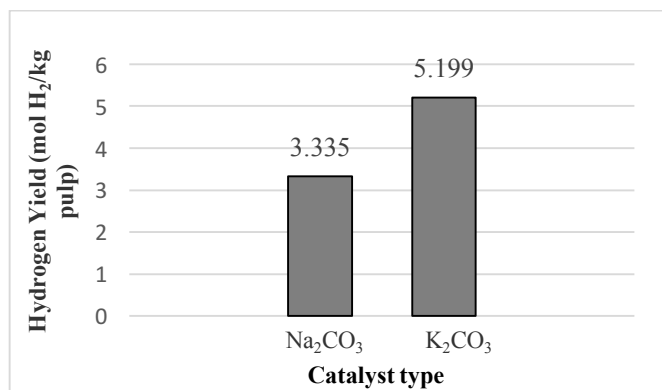

Fig. 5. Influence of catalyst type on hydrogen yield obtained from gasification of pulp (650°C, 20 wt. % catalyst, 2 L/h air flow rate, 15 min. reaction time)

Catalytic performance of K_2CO_3 on the carbon conversion efficiency and gas LHV has been studied with different catalyst loading. According to Table 3., there was no significant increase in gas yield if the catalyst ratio was increased from 20 to 40 wt.%. However, irrespective of the catalyst ratio, carbon conversion efficiency remained almost

the same. Besides, the highest value of LHV was obtained in the presence of 30 wt.% catalyst as 9842 kJ/STP m³.

Table 3. Experimental result of different catalyst ratio (650°C, 2 L/h air flow rate, 15 min. reaction time)

Catalyst ratio (wt. %)	0	20	30	40
Gas yield (STP m³/kg biomass)	0.740	0.775	0.785	0.800
Carbon conversion efficiency (%)	84.716	80.805	81.549	81.081
Gas LHV (kJ/STP m³)	10263	9226	9842	9741

Fig. 6. shows the gas composition of pulp gasification depending on various catalyst ratio. As hereinbefore stated, hydrogen content increased greatly from 3.220 to 5.199 mol H_2/kg pulp with 20 wt.% catalyst. However, a further increase in the catalyst ratio changed the selectivity towards H_2 and caused a fall. Conversely, the addition of 20 wt.% catalyst led to a considerable reduction in CH_4 content. Using a catalyst promotes tar cracking reactions, steam reforming and water-gas shift reactions [36]. Therefore, the increase in H_2 and fall in CH_4 can be due to the contribution of these reactions. In addition, CH_4 continued to exhibit a descending trend with 40 wt.% catalyst addition. Unlike H_2 and CH_4, CO content showed exactly the opposite tendency and continuously increased by a varying catalyst. Despite the fact that CO_2 content remained constant in the absence of a catalyst and the presence of 20 wt.% catalyst, it reached a maximum value of 6.640 mol gas/kg pulp with 40 wt.% catalyst. The ethane-propane yield reduced by increasing the catalyst loading to 20 wt.%, and further catalyst loading showed an insignificant chance in ethane-propane yield. The comparison results from both temperature and catalyst effect cases on pulp gasification revealed that temperature became more effective on product gas composition within the range studied in this work. Therefore, more carbon conversion, gas yield and gas LHV were achieved by increasing temperature. However, K_2CO_3 catalyst by 20 wt.% also showed a significant promotion role to improve the hydrogen yield.
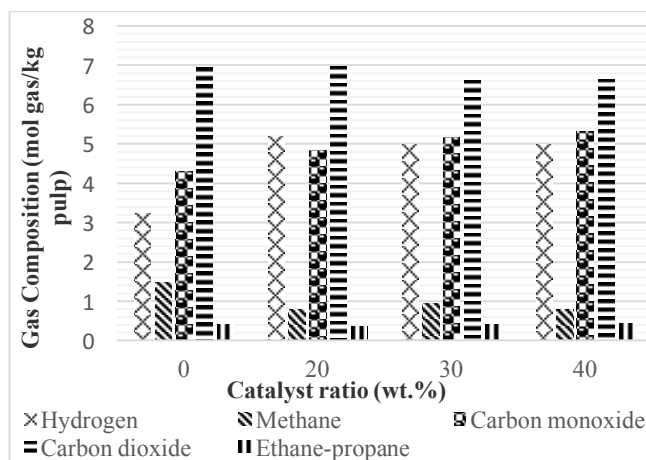

Fig. 6. Influence of catalyst ratio on gaseous product composition (650 °C, 2 L/h air flow rate, 15 min. reaction time)

Although producer gas is the predominant product, some part of biomass decomposes into char and tar during the gasification process. According to the decision made at the European Union/International Energy Agency/United States Department of Energy (EU/IEA/USA-DOE) meeting, the term tar is defined as all organic contaminants whose molecular weight is higher than benzene [37]. Char is the carbonaceous solid left behind biomass gasification and has a high calorific value [38]. From this point of view, the purpose of the gasification process is to yield maximum gas production that can be possible by the elimination of tar and char formation. However, tar elimination reactions are kinetically limited and involve temperature and/or catalyst to faster the reaction rate [39].

Figure 7. represents the effect of temperature on the gasification product (gas, tar and char) distribution. As can be seen from this figure tar and char amount rapidly went down with the temperature rising from 650 °C to 750 °C, thus causing a notable increase in gas yield. Char yield reduced dramatically from 30.921 to 3.514 wt.%, whereas tar yield decreased from 31.650 to 4.815 wt.% in the studied temperature range. This indicates that tar cracking and char conversion were encouraged due to temperature rising. Both tar and char yield continued to reduce with further rising of the temperature and were found to be 2.542 and 4.283 wt.% at 850 °C, respectively. The reduction in tar and char resulted in a corresponding increase in gas yield, thus achieving 93.180 wt.% gas yield at 850 °C.
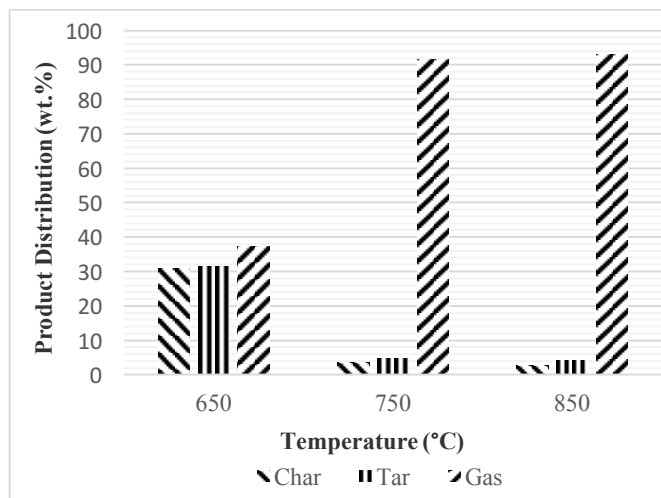

Fig. 7. Influence of temperature on product distribution (without a catalyst, 2 L/h air flow rate, 15 min. reaction time)

The change in gas product distribution with catalyst ratio is summarized in Figure 8. As observed in Fig. 8. catalyst exhibited a different tendency on product distribution by comparison with the temperature. Char conversion gradually was enhanced by further addition of the catalyst and a small amount of char remained in the 40 wt.% catalyst. In addition, the highest tar yield was obtained as 31.473 wt.% in the presence of 20 wt.% catalyst and it showed a significant decline in the range of 20-40 wt.% catalyst. However, the gas yield continually raised along with the increasing catalyst loading, and maximum gas yield was achieved with 40 wt.% catalyst loading as 89.554 wt.%. Comparing the cases with and without a catalyst, it could be seen that raising the temperature is relatively more effective to minimize tar and char yield hence advancing gas yield.
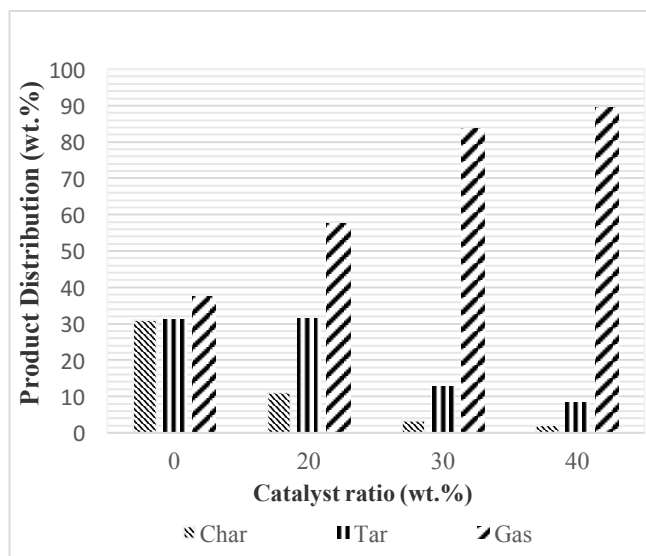

Fig. 8. Influence of catalyst ratio on product distribution (650 °C, 2 L/h air flow rate, 15 min. reaction time)

3.2.2. Gasification of WUNESB, stalk and waste mixture

During the processing of sugar beet, there is not only sugar beet pulp is left behind, but also stalk and WUNESB are separated prior to sugar beet being sent to the extraction system. This all waste from the sugar industry creates an opportunity for the production of energy thus reducing environmental concerns. Therefore, this study was extended to assess WUNESB, stalk and their mixture as feedstock for hydrogen-rich gas production.

WUNESB, stalk and waste mixture were gasified at 650 °C, 20% K_2CO_3 and 15 min. reaction time. The results found (hydrogen yield) were compared with the results of pulp (Fig. 9). The physical and chemical composition of biomass is an important parameter for gasification process performance. Cellulose, hemicellulose and lignin are the main components of biomass. Furthermore, cellulose and hemicellulose content are related to producer gas yield [40]. From Fig. 9., it is observed that pulp hydrogen content is relatively higher compared to the mixture and other sugar beet waste. This result indicated a good agreement existed between proximate analysis and parametric study of pulp since it contains a high proportion of cellulose and hemicellulose as shown in Table 1. In addition, the hydrogen yield of WUNESB and the mixture that contains equal amounts of wastes of sugar beet are fairly close to each other and have found to be 4.663 mol H_2/ kg WUNESB and 4.816 mol H_2/kg mixture, respectively. However, stalk hydrogen yield, on the other hand, was not a desirable result with a value of 2.700 mol H_2/kg stalk. This might be ascribed to the following reasons; a lower proportion of cellulose and hemicellulose content and large amounts of extractives content in the stalk that could have led tar formation instead of the gaseous product.
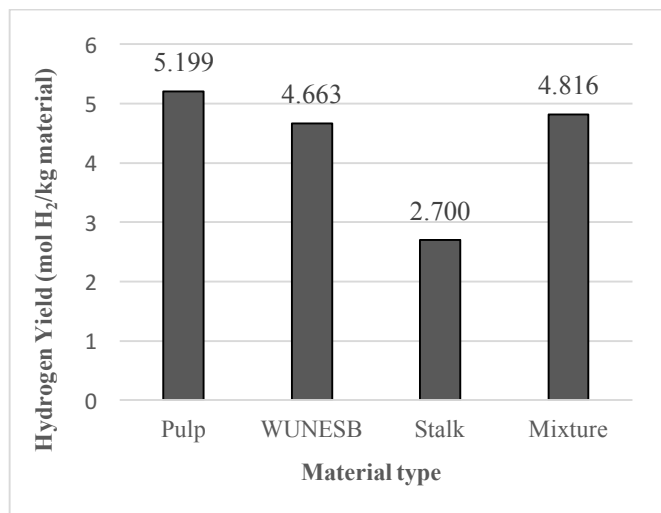
Fig. 9. Hydrogen yield of pulp, WUNESB, stalk and mixture (650 °C, 20 wt.% K_2CO_3, 2 L/h air flow rate, 15 min. reaction time)

4. Conclusion

Special attention has been recently paid to biomass gasification to generate producer gas that might be an alternative for reducing the reliance on fossil fuels. The present study was focused on gasification of sugar beet wastes in updraft tubular gasification reactor using air as a gasifying agent for producing hydrogen-rich gas. The effect of experimental parameters on gas yield, gas composition, carbon conversion efficiency, gas LHV were analyzed and results given as follows;

Temperature appeared to be the most salient factor in pulp gasification. It was concluded that hydrogen yield continuously improved with raising reaction temperature within 650-850 °C range in which its growth rate reached as high as 78% without a catalyst. Furthermore, the higher temperature resulted in the higher gas yield and 0.900 STP m^3/kg pulp attained at 850 °C. The trend in the carbon conversion efficiency of pulp gasification is similar to gas yield, and its maximum value was obtained at 850 °C as 95.061%. The increasing temperature did not always affect gas LHV positively since low gas LHV was obtained at 750 °C compared to 650 °C, while the highest value of gas LHV was attained as 10298 kJ/STP m^3 at 850 °C.

Under the catalytic conditions, the highest hydrogen yield was achieved at 20 wt.% catalyst (K_2CO_3) as 5.199 mol H_2/kg pulp. Moreover, different catalytic effects on hydrogen yield in pulp gasification were investigated, and it was found that the type of catalyst had a notable effect on the hydrogen yield. Under the same operating conditions, Na_2CO_3 catalyst exhibited lower levels of activity in terms of hydrogen production. On the other hand, gas yield continued to increase with the small increment as catalyst ratio increased, and the highest gas yield achieved as 0.800 STP m^3/kg pulp. Additionally, the highest carbon conversion efficiency and gas LHV were respectively obtained as 81.549% and 9842 kJ/STP m^3 in presence of 30 wt.% K_2CO_3 catalyst.

The mixture which contains equal quantities of pulp, WUNESB and stalk was utilized to determine hydrogen yield, and it was found to be 4.816 mol H_2/kg mixture at 650 °C with 20 wt.% K_2CO_3. It is fairly close to the yield obtained from pulp under the same operating condition. This means that all waste material taken from the sugar factory can be directly used without any separating.

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