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Experimental investigation of a downdraft gasifier for efficient syngas production using Iraqi waste

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ABSTRACT

The purpose of this study is to investigate the gasification of Iraqi corn cobs and wood using the GEK Power Pallet downdraft gasifier, using both feedstocks individually and in mixtures. The experiments were conducted at an equivalence ratio of 0.35, a biomass feeding rate of 5 kg/hr, a gasifier temperature range of 750 to 1000 °C, and an atmospheric pressure of 1 atm. The syngas composition, Thermogravimetric analysis (TGA), and tar behavior were analyzed for each feedstock. It was observed that corn cobs resulted in a higher H2 content in the syngas of 13.8% and CO of 17%. In contrast, wood showed a higher CO content of 19.3%. The corn cobs yielded a low tar content of 1.30 mg/Nm^3, followed by the 30:70 wood-corn blend which had a tar content of 1.33 mg/Nm3. In regard to cold gas efficiency, corn cobs had the most efficient CGE (71.91%) followed closely by the 70% corn blend (68.31%). The TGA results for corn exhibited rapid devolatilization, while wood showed a higher char residue. In summary, this study demonstrates the potential for Iraqi-origin biomass in small-scale gasification systems while identifying a potential benefit to the blending of different feedstocks to optimize syngas characteristics or operational dependability.

Keywords: biomass gasification, syngas production, thermogravimetric analysis, downdraft gasifier, Iraqi biomass.

INTRODUCTION

Alongside climate change concerns, the increase in global energy demand linked with the rise in global population and improvement of living conditions has changed the energy perspective towards renewable energy sources [1]. The increasing debate towards climate change, greenhouse gas emissions, and the demand for energy makes using renewable energy sources one of the key approaches for sustainable power generation [2]. Compared to conventional fossil fuel sources, biomass exhibits a lower environmental impact and is inherently sustainable [1]. Among the available thermochemical conversion methods, gasification offers distinct advantages: it transforms biomass into a combustible gas mixture (syngas) that can be used for heat and power generation or as a feedstock for synthetic fuels and chemicals [3,4]. Syngas is a flexible energy source that is produced from biomass. It consists of hydrogen (H_2), carbon monoxide (CO), and additional gases. It facilitates diverse energy uses, serving to generate heat and electricity, and as a raw material for fuels and chemicals also, for energy purposes, syngas finds uses in internal combustion engines, gas turbines, and fuel cells, producing electricity more efficiently than direct burning biomass [5]. Due to their low tar content in producer gas and ease of construction and operation, downdraft gasifiers represent a very appealing technology [6]. The conversion efficiency of the downdraft fixed-bed gasifier has been reported as 60–80% in most previous studies while exhibiting lower thermal efficiency produces significantly cleaner gas suitable for engine applications. Prior study [7] completed an experimental study with a three air-stage continuous fixed-bed downdraft gasifier to determine how geometric design and operational parameters, specifically the equivalence ratio and feeding rate, impacted the quality of syngas produced. Their results suggest that three air stage provided higher temperatures within the oxidation and reduction zones of the gasification process and subsequently improved tar-cracking efficiency. [8] evaluated the performance of a 24 kWe downdraft gasifier using sugarcane bagasse and coconut shells as input feedstock. The equivalence ratio (ER) varied for each testing regime in relation to feed rate. The results showed that coconut shells produced less tar compared to bagasse, that sugarcane bagasse produced a higher volume of syngas compared to coconut shells, indicating how fuel type can affect gasification efficiency and subsequent syngas characteristics when operational conditions vary. In another experiment, [9] examined the gasification of rice briquettes mixed with grounded cotton stalks in an Imbert gasifier, specifically observing how airflow rate would affect the performance of the gasifier. They show that increasing the airflow rate significantly increased the fuel consumption rate by 63.3% demonstrating how sensitive gasification processes were to the operational parameters of airflow. The gasification of various biomass types, including rice husks, corn stalks, and wood chips, under various operating conditions, has been the subject of numerous studies. Regional studies on Iraqi-origin biomass gasification are limited, and there is a lack of experimental data on how local biomass composition and operating parameters affect syngas yield, heating value, and tar content under controlled gasification conditions. Furthermore, there aren't many performance reviews of the GEK Power Pallet gasifier in Middle Eastern-specific settings or under Iraqi specific environmental and resource conditions. Although biomass gasification has advanced, not much is known about how local biomass properties and gasifier design affect syngas yield and quality. Therefore, the aim of this study is to investigate, under fixed operating conditions, the syngas production potential of corn cobs and wood biomass using a downdraft gasifier (GEK Power Pallet). The effect on syngas composition and calorific value of biomass properties, gasifier temperature, air flow rate, and equivalence ratio is investigated here, in contributing a new dataset to the regional literature and enabling the possibility of incorporating small-scale biomass gasification systems into Iraq's renewable energy plan in the future, it establishes a baseline of local biomass conversion performance. The results assist in determining whether it is feasible to include local biomass in small-scale gasification systems in Iraq and other similarly arid areas.

MATERIALS AND METHODES

Feedstocks preparation

The feedstocks chosen for this study were corn cobs and wood residues from a local farm in Diyala Governorate. These feedstocks were cut to pieces, approximately 5–7 cm, and dried in a laboratory oven at 105 °C for 2 hours to lower moisture content below 10%. To obtain a complete characterization of the feedstocks, proximate and ultimate analyses were run, and all necessary information about the characteristics, moisture, volatile matter, fixed carbon, ash, and elemental composition of the feedstocks (C, H, N, O, S). All was detailed according to ASTM D3172–13 (proximate) and ASTM D3176–15 (ultimate) standards. The results of this analysis are included in Table 1.

Gasifier description

The gasifier explored in this study, a multi-stage downdraft gasifier (GEK Power Pallet, All Power Labs), is a thermal integration design based upon the Tower of Total Thermal Integration (TOTTI). The entire unit is mounted on a compact skid base with dimensions of 1.2 × 1.2 × 1.8 m for the 10 kW model that was used in this experiment. It consists of a multi-stage gasifier, spark fired industrial engine, feeding system, generator head, and process control unit (PCU). The PCU monitors and responds to all internal reactor, engine, and filter conditions, including temperature and pressure displaying the results

Table 1. Proximate and ultimate analysis

Parameter	Units	Corn cobs	Wood
Moisture	%	6.3	4.19
Volatile matter	%	90.65	95.19
Fixed carbon	%	25.44	23.6
Ash content	%	2.28	0.39
C	%	43.6	48.2
H	%	6.3	6
O	%	46.8	45.8
N	%	9.5	6.1
HHV	kJ/kg	17.61	19.05

on an LCD screen. The reactor is divided into four main zones (drying, pyrolysis, oxidation, and reduction). The temperature of each zone was continually measured using K-types of thermocouples, which were placed at different heights of the gasifier. The average temperatures for steady state operation were approximately 250–300 °C (drying), 400–600 °C (pyrolysis), 900–100 °C (oxidation) and 700–800 °C (reduction). The gasifier was operated at atmospheric pressure (1 atm) and air was used as the gasifying medium. In this type of furnace, the product of the pyrolysis zone flows through the combustion zone, where the temperature is high, it breaks down into gas before dropping from the stove [10]. This design incorporates several integrated features designed to improve overall thermal efficiency including, a PyroCoil, which recovers heat energy from the engine exhaust; a double-jacketed drying bucket used as pretreatment when fuel is too wet; an air preheat and syngas cooling system that combines drying, heating, and cooling. Figure 1 shows the GEK Power Pallet. The integrated systems improved the capacity to process fuels with differing moisture contents and improved tar conversion efficiency significantly. The biomass feed system included a stainless-steel hopper capable of holding enough biomass fuel to maintain continuous operation for an estimated 10 hours.

Experimental conditions

Experiments were carried out at atmospheric pressure (1 atm) and air as a gasifying agent at an equivalence ratio (ER) of 0.35 for optimum performance and stability, according to the recommendation of [11]. Biomass was fed continuously at a feed rate of 5 kg/h, while ambient air was employed as the gasifying medium, at a flow rate of 30 m^3/h. Reactor temperature was carefully monitored using a K-type thermocouple installed in the oxidation zone and maintained steadily around 760 °C throughout each experimental run. The calculated gas residence time in the reduction zone was 2–4 seconds with the model being based on the gas velocity and reactor volume. Four different feedstocks were examined: pure corn cobs, pure wood chips, a mixture of 70% corn cobs and 30% wood chips, and another mixture of 70% wood chips and 30% corn cobs. All the operations parameters, such as airflow rate, solid biomass feeding rate and the ER remained constant throughout all experiments. Each gasification experiment lasted between 50 and 55 minutes, with 15 minutes being the startup, then a steady period lasting 40 to 42 minutes for gas sampling, and a cooling phase at the end. The steady operational period was identified when stable temperatures were recorded and a consistent syngas composition was observed. The Gasboard-3100P analyzer was used to detect the syngas composition, it is a portable gas analyzer that combines NDIR (non-dispersive infrared), TCD (thermal conductivity; MEMS TCD in some docs) and electrochemical sensors to measure combinations of: CO, CO_2, CH_4, H_2, O_2, total hydrocarbons (CnHm) and optional species (e.g., C_2H_2, C_2H_4). It was connected to the GEK system by a small valve that is placed after the filter using the flexible pipe of the analyzer. It measured the syngas composition for the

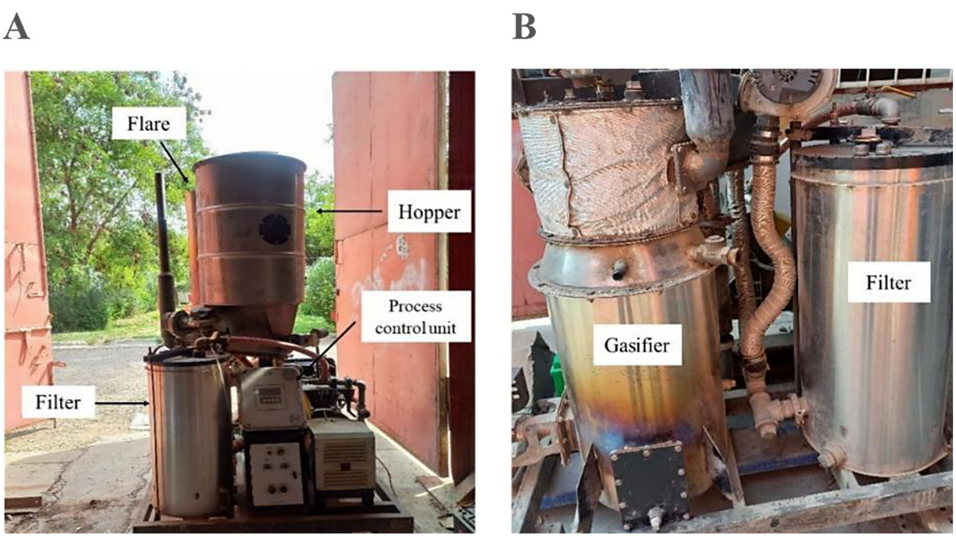

Figure 1. (a) The GEK power pallet; (b) The gasifier and filter

full time of operating analyzing CO, CO_2, H_2, and CH_4, as the data was recorded for every 200 °C.

RESULTS

This section presents the experimental results obtained from the gasification of Iraqi maize cobs and wood and their mixtures on the GEK power pallet downdraft gasifier. It include a quantitative analysis of the results together with the thermochemical interpretation and a comparison with previous research done in this area. All the figures presented have been repeated three times with an average deviation of less than ±5%.

Thermogravimetric analysis

Thermogravimetric analysis (TGA) (Figure 2) was conducted to explore the thermal decomposition behavior of corn cobs and wood chips under controlled heating conditions so as to improve understanding of their pyrolysis nature and performance characteristics (appropriate for gasification). Figure 3 shows the weight loss curves for both feedstocks, as the corn sample was 2.9 mg and had a total weight loss of 97.45% while the wood sample was 1.97 mg and had a total weight loss of 99.78%. Thus, based on TGA results, for corn there was more weight lost and a smaller char remaining after run completion. The residual mass was 2.55% for corn and 0.22% for wood at 1000 °C, with corn yielding slightly more char than wood. The result of the TGA runs provide an additional explanation of operational behaviors while gasifying corn in comparison to wood feedstock; corn has fast devolatilization rates which yield high gas yields and create steep heat demand requirements, and wood has slower char conversion and is more stable in the reduction zone. These results agree with [12] and [13] previous studies.

Syngas composition

The data show a clear trend where the methane concentration initially rises with increasing temperature, reaches a peak around 400–500 °C, and subsequently decreases as temperatures continue to rise towards 1000 °C. This behavior is

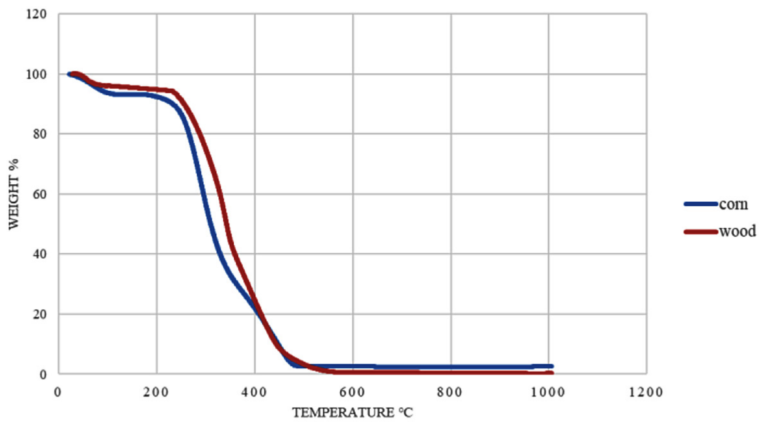

Figure 2. Thermogravimetric analysis (TGA) of corn cobs and wood

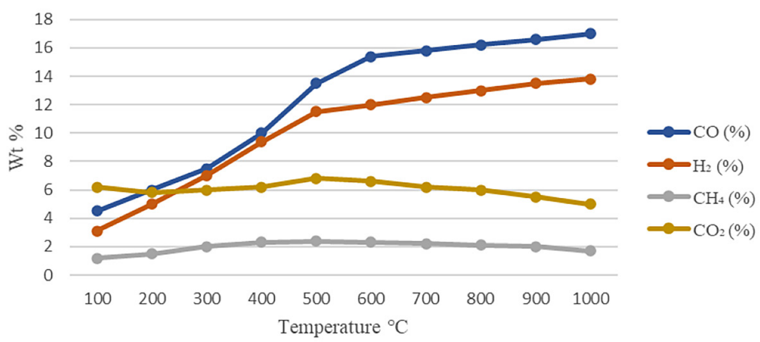

Figure 3. Corn cobs syngas composition results

consistent across all tested biomass types and mixtures, highlighting the characteristic pattern of methane formation and decomposition during gasification processes.

Corn cobs

The first case included using 5 kg of corn cobs only. The syngas produced in this case using corn cobs at an ER of 0.35 and a gasification temperature of 760 °C contained 17% CO, 13.8% H_2, 6.8% CO_2, and 2.4% CH_4. At low temperatures, incomplete thermal decomposition limits CO formation. However, as the temperature rises above 400 °C, the Boudouard reaction and steam–carbon reaction become thermodynamically favored. These endothermic reactions consume CO_2 and char, producing additional CO. The increase in H_2 concentration with temperature indicates the dominance of these endothermic reactions at high temperatures. CH_4 is primarily produced during the pyrolysis phase (below 500 °C) from volatile matter. At higher temperatures, CH_4 undergoes thermal cracking and reforming, reducing its content. Initially, CO_2 is produced from the oxidation of carbonaceous matter and decomposition of oxygen-containing functional groups. These results are comparable to those reported by [14] who gasified corn stover under similar conditions, obtaining a syngas with 15.6% H_2, 14.6% CO, 14.5% CO_2, and 1.6% CH_4. The slightly higher hydrogen yield in the present study may be attributed to the higher moisture content (14.7%).

Wood

The second case used wood only with same amount (5 kg). The gasification of wood under the same conditions resulted in composition of 19.3% CO, 6.7% CO_2, 12.1% H_2, and 1.5% CH_4. Methane and hydrogen content is higher than those reported by [15] who used mahogany and mango wood under ER of 0.34. The CO content was slightly higher than corn cobs. Wood's higher lignin content and lower volatile matter cause fewer releases and thermal cracking of light hydrocarbons, which is the main reason why wood syngas has lower hydrogen and methane than corn cob syngas. Conversely, under the same circumstances, the biochemical composition of corn cobs encourages increased devolatilization and the production of hydrogen-rich gases (Figure 4).

30% wood / 70% corn cobs

In a third case, a biomass input of 5 kg was used, 30% of which was wood and 70% was corn cobs, using the same ER and temperature range as before. Notably, shows CO and H_2 concentrations closer to pure corn cobs, demonstrating the great effectiveness of corn cobs in their effect of promoting CO formation. This phenomenon can be attributed to the endothermic characterization of reactions such as Boudouard´s reaction ($C + CO_2 = 2CO$) and char-steam reaction ($C + H_2O = CO + H_2$), which are thermodynamically favored at high temperatures, and enhance the formation of CO and H_2. On the other hand, the exothermic methanation ($CO + 3H_2 = CH_4 + H_2O$) and water-gas shift reaction are backward at increased temperature which gives rise to diminished yields of CO_2 and CH_4. The slight increase of CH_4 at temperatures up to about 500 °C may be due to volatile matters given off and incomplete reforming during pyrolysis followed by lower amounts of CH_4 at increased temperatures due to methane reforming by steam and thermal cracking. However, it was lower compared to wood. This mixture gives a syngas which has a considerable balance of good concentrations of both CO and H_2, demonstrating the advantage of

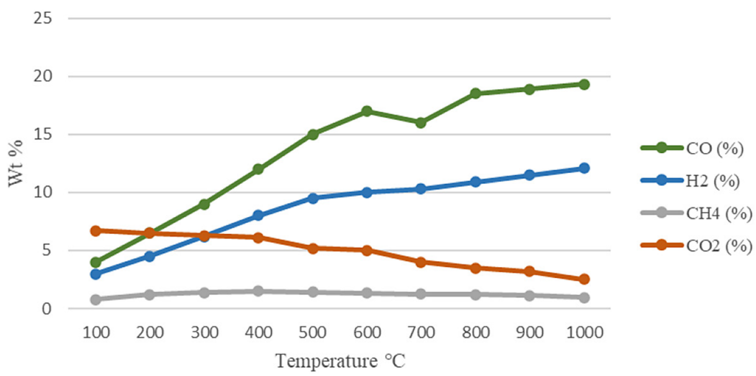

Figure 4. Wood syngas composition results

using a mixture of high-volatile and high carbon feedstocks (Figure 5).

70% wood / 30% corn cobs

The last case was using 70% of waste as wood and 30% of corn cobs. mixture shows a lower CO and H2 content of 10.8% and 7.8% respectively. This blend, dominated by wood, produces a syngas with modest energy content but high thermal stability, making it suitable for consistent operation under varied conditions. CH_4 exhibits a slight increase at moderate temperatures (ca. 300–500 °C) which is probably due to devolatilization and methanation of intermediate products followed by decline at higher temperatures where methanation reactions converts methane into CO and H_2 through reforming and cracking of methane. In a summary, increasing the gasification temperature gives a greater yield of combustible gases (CO and H_2) and less CO_2 and CH_4 giving rise to better calorific values of the syngas indicating more complete carbon conversion of the 70% wood – 30% corn cob mixture. Overall, these observations emphasize the significant effect of biomass composition on syngas quality, with corn cobs proving to be particularly effective in H_2 generation compared to wood. The results underline the importance of optimizing biomass selection and blending ratios for achieving desired syngas characteristics in practical gasification applications (Figure 6).

Tar behavior

The data showed that wood gasification yields the highest tar yield of all of the feedstocks tested, showing that wood possesses a greater potential for tar generation than the other feedstocks under these experimental conditions. Corn cobs yield significantly lower quantities of tar, making them a favorable biomass option to reduce the impact of tar related operational issues with gasification. The blended mixtures of feedstocks as hybrid fuel sources provide moderate tar yields with respect to 100% wood or corn cobs. The blended fuel source exhibited that 70% wood had a moderate yield of tar as a gas, more than the 30% wood blended mixture, confirming that an increase in wood content of blended fuel source relates to increasing tar production. Overall, these results highlight the substantial influence that feedstock has on the overall tar yield in biomass gasification processes suggesting that intentional feedstock selection or blend of feedstocks will be an effective approach to optimize performance and improve quality of syngas (Figure 7).

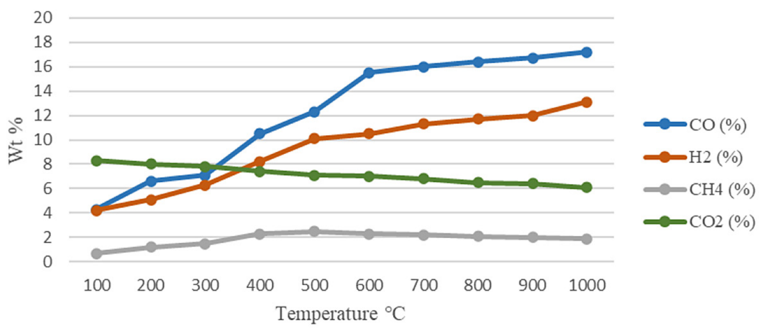

Figure 5. 30% wood / 70% corn cobs syngas composition results

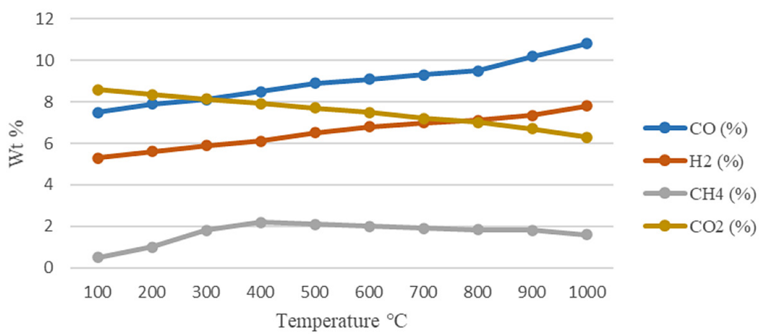

Figure 6. 70% wood / 30% corn cobs syngas composition results

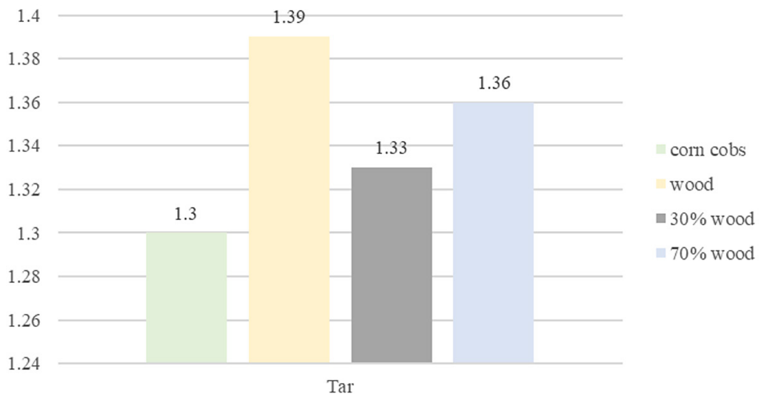

Figure 7. Tar results for different feedstocks used

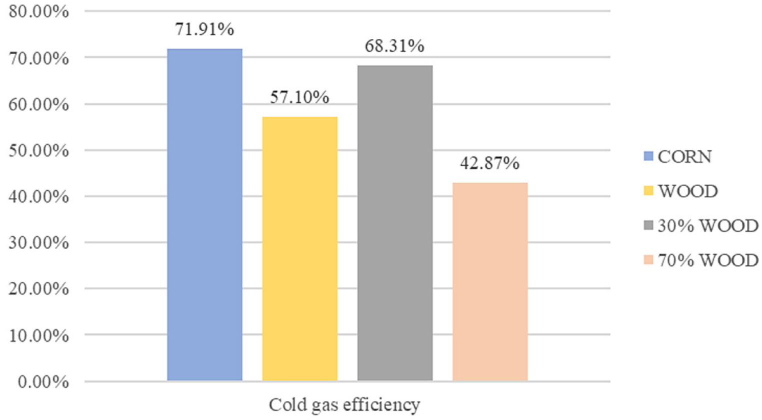

Figure 8. The cold gas efficiency of syngas

Cold gas efficiency

The cold gas efficiency is a key measure in biomass gasification, which is defined as the ratio of the chemical energy retained in the produced syngas to the chemical energy of the original feedstock. It describes how efficiently the gasifier has converted solid biomass into a useful gaseous fuel. Observing Figure 8, Corn cobs reached the highest cold gas efficiency (CGE) value of 71.91%, suggesting superior energy conversion efficiency that is higher than [16] results. Pure wood had the lowest CGE value of 57.1%, which is highly similar to [16] findings as the CGE of wood briquettes was 57.91%. This result is consistent with its lower heating value observed for wood syngas. The 30% wood / 70% corn blend exhibited a similar CGE value of 68.31%, nearly on par with pure corn, suggesting as long as the corn ratio remains high, the system can maintain high energy conversion performance. In contrast, the 70% wood / 30% corn blend exhibited a CGE of 42.87%. The cold gas efficiency results correlate well with the lower heating values, supporting the conclusion that corn cobs are more effective than wood in the tested conditions. Ultimately, this research supports the clearly important consequences of the chemical composition and the molar behavior of the ash in predicting gasifier performance, rather than simply the basic proximate values of each feedstock.

CONCLUSIONS

This study examined the gasification performance of corn cobs and wood biomass from local sources using a downdraft gasifier (GEK Power Pallet) under fixed operating conditions. The analysis of thermal, compositional, and operational information provided useful information regarding the relationship between feedstock type and blending ratios on syngas quality and tar production; which offers a greater understanding of the potential of these types of biomass resources for clean and efficient energy production and their suitability in decentralized and sustainable power systems.

TGA data showed dramatically different thermal decomposition results between biomass feedstocks. Corn cob feedstock devolatilized more quickly than wood and had higher char residue, thus providing more gas yield. This showed that corn cobs have a more demanding heat requirement during gasification. Wood devolatilized much more slowly, and char residue was negligible, indicating a more thermally stable feedstock in the reduction zone.

The comparative results indicated that biomass type and blending ratio affect syngas composition. Corn cobs produce hydrogen-rich gas with desirable properties because of the volatile fraction found in the biomass. Wood favors CO production because of its higher fixed carbon fraction. Finally, blending feedstocks allows the feedstock compositions to be tuned accordingly to produce the required gas compositions for reliable syngas use, such as combustion in internal combustion engines and synthetic fuel production. Performance of gasification was optimal in all cases when temperatures were > 600 °C, where CO and H_2 percentage concentrations were greater than the other gases, and the formation of tars was diminished.

Tar production analysis indicates that the overall management of tar requires a complete control of temperature. Tar production begins to reduce significantly above 500 °C and reaches almost complete cracking at 700 °C. Corn cobs produce less tar than low-lignin wood supports, with blends between low-lignin wood/corn cobs yielding the most flexibility in terms of all syngas qualities and tar management. This research supports strong thermal management of the downdraft gasifier and supports the sustainability of using feedstocks with high volatiles and low lignin (e.g., corn cobs) to produce clean syngas.

With regard to cold gas efficiency, corn cobs had the most efficient CGE (71.91%), followed closely by the 70% corn blend (68.31%). Wood had a CGE of 57.1% and the 70% wood blend had the least efficient CGE of 42.87%.

Although this study provides valuable baseline data, future investigations should include (1) continuous long-duration operation to assess stability, (2) detailed tar speciation and energy balance modeling, and (3) the use of advanced gas cleaning or catalytic reforming systems to further enhance gas quality.

Overall, this work provides a practical foundation for selecting biomass feedstock in small-scale gasification systems aimed at a sustainable energy resource.

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