Gasification performance of switchgrass pretreated with torrefaction and densification

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HIGHLIGHTS

• We evaluated effects of switchgrass torrefaction and densification on the syngas.
• The pretreatment and gasification temperature significantly affected performance.
• Combined torrefaction and densification had the highest gas yield and efficiencies.
• Increase in gasification temperature increased the gas yield and efficiencies.

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ABSTRACT

The purpose of this study was to investigate gasification performance of four switchgrass pretreatments (torrefaction at 230 and 270 °C, densification, and combined torrefaction and densification) and three gasification temperatures (700, 800 and 900 °C). Gasification was performed in a fixed-bed externally heated reactor with air as an oxidizing agent. Switchgrass pretreatment and gasification temperature had significant effects on gasification performance such as gas yields, syngas lower heating value (LHV), and carbon conversion and cold gas efficiencies. With an increase in the gasification temperature, yields of H2 and CO, syngas LHV, and gasifier efficiencies increased whereas CH4, CO2 and N2 yields decreased. Among all switchgrass pretreatments, gasification performance of switchgrass with combined torrefaction and densification was the best followed by that of densified, raw and torrefied switchgrass. Gasification of combined torrefied and densified switchgrass resulted in the highest yields of H2 (0.03 kg/kg biomass) and CO (0.72 kg/kg biomass), highest syngas LHV (5.08 MJ m⁻³), CCE (92.53%), and CGE (68.40%) at the gasification temperature of 900 °C.

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1. Introduction

The increase in the world population to 7 billion and further projected increase to 10 billion has increased awareness about the need of more resources to supply energy, food and other consumable products [1]. Currently, a huge proportion of the demand for energy and chemicals are met by fossil fuels that are non-renewable, increase greenhouse gas (GHG) emissions and make many countries heavily dependent on import. The fossil fuels can be replaced with second generation biofuels, derived from lignocellulosic feedstocks, agricultural residues and their byproducts [2]. Biomass, an organic plant-based material, converts solar energy and carbon dioxide into chemical energy through photosynthesis. Since sunlight is a sustainable resource, biomass can be generated through photosynthesis on a sustainable basis, which makes the biomass a renewable resource that can be utilized worldwide.

Switchgrass (Panicum virgatum L.), a native North American perennial lignocellulosic grass grown in the central USA is one of the ideal biomass feedstocks due to its high crop yield (10–12 t/ha/annum) [3], adaptation to soil and climatic conditions and minimal requirement of fertilizers to grow the biomass [4,5]. However, certain properties of switchgrass [3] (similar to the properties of other biomass feedstocks) such as high moisture content, low bulk density, high caloric value, high volatile and oxygen contents, and its tenacious and fibrous nature create challenges to store the biomass for long hours, to transport and convert efficiently into fuels and other products [6,7]. Pretreatments such as torrefaction and densification have potential to improve the properties of biomass such as switchgrass making it a better feedstocks for conversion
into fuels and chemicals [8]. Torrefaction, a thermochemical process, taking place at temperatures ranging between 200 and 300 °C in an inert atmosphere, produces a hydrophobic product which prevents the biomass from getting decomposed when exposed to the atmosphere [9]. The product obtained also has higher heating value (HHV) and a high energy density [10]. Densification converts loose biomass into pellets having less fines, high uniformity and high bulk density that can possibly solve challenges in storing and transporting biomass [11,12]. A combination of torrefaction and densification may further increase conversion efficiency, and reduce storage and transportation costs as this pretreatment leads to a more uniform hydrophobic product with high energy and bulk densities [6,13,14].

The second generation biofuels are produced through two distinct conversion processes namely the biochemical and thermochemical conversions. The biochemical conversion consists of enzymatic transformation of cellulose and hemicellulose to sugars and further fermentation into ethanol and higher alcohols [2,15], whereas, the thermochemical conversion uses heat and catalysts to convert biomass into intermediate products, syngas and biooil through gasification and pyrolysis, respectively [16]. The syngas (gasification intermediate) is composed of carbon monoxide, carbon dioxide, hydrogen, nitrogen (if air is used as oxidizing agent), and small quantities of hydrocarbons such as methane, ethane etc. The syngas can further be converted into useful fuels (gasoline and diesel), chemicals (methanol and ethanol) through catalytic and microbial processes [17]. The gasification can take place in a variety of reactors such as fixed bed (updraft, downdraft and cross draft, batch) and fluidized bed (bubble and circulating) gasifiers [18]. Fixed bed gasifiers are advantageous over fluidized bed gasifiers especially for small scale applications as the design of fixed bed gasifiers is simple, less expensive and are suitable for biomass combustion, biomass gasification, small scale power generation and industrial heating applications [19]. Fluidized bed gasifiers (FBG) are more suitable for large scale applications because of their higher mass and heat transfer efficiencies but FBG are also more complex in design and operation as compared to fixed bed gasifiers [20]. This paper reports study on a fixed-bed gasifier.

The gasification performance of raw and pretreated biomass can be evaluated based on the concentration and yield of syngas, and energy and carbon conversion efficiencies. Gasification performances of several types of raw biomass feedstocks and gasifiers have been extensively reported in literature [21–30]. Limited studies have also been reported on gasification of pretreated biomass except switchgrass [7,31,32]. Bibens [7] investigated the downdraft gasification performance of pine chips torrefied at 250, 275 and 300 °C for 30 and 60 min and concluded that at a gasifier temperature of 800 °C and an equivalence ratio (ER) of 0.25, with an increase in the torrefaction temperature and time, the syngas HHV, and syngas yield and net energy output per unit of material increased. By fluidized-bed air gasification of raw and torrefied (at 250 and 300 °C) wood at a gasifier temperature of 950 °C, Prins et al. [31] observed that the overall exergetic efficiency of torrefied wood was lower than of raw wood because part of the biomass energy was lost in volatiles during torrefaction. With high-temperature air/steam gasification of densified wood pellets in an updraft gasifier using preheated air and steam, Lucas et al. [32] observed that an increase in the gasifier temperature from 350 to 900 °C increased the gas yield and HHV, and reduced production of tars, soot and char. However, to our knowledge, there is no literature available on gasification of switchgrass pretreated with torrefaction and densification.

The goal of this study was to investigate the effects of four pretreatment (torrefaction at 230 and 270 °C, pelletization, and combined torrefaction and pelletization) and three gasification temperature (700, 800 and 900 °C) on the gasification performance of switchgrass.

2. Materials and methods

2.1. Biomass feedstock

Kanlow Switchgrass (P. Virgatum) grown at the Plant and Soil Sciences department at Oklahoma State University was used as the biomass. Bales of Kanlow switchgrass were chopped using a Haybuster tub grinder (H1000, Duratech Industries International Inc., Jamestown, N.D) with a screen size of 25 mm. A portion of chopped switchgrass was further ground using a hammer mill (Bliss Industries, Ponca City, Oklahoma) with a mesh size of 4 mm. Chopped switchgrass was used for all torrefaction pretreatments and ground switchgrass was used for pelletization (densification) pretreatments at the Idaho National Laboratory (INL, Idaho Falls, Idaho).

2.2. Torrefaction

A moving-bed gravity-fed atmospheric pressure thermal treatment system was used to torrefy switchgrass (Fig. 1). It consisted of horizontal auger-driven sections to feed material into and out of a vertical, central reactor with diameter and height of 0.305 and 1.68 m, respectively. The details and schematic of the torrefaction unit can be found elsewhere [33]. The ground switchgrass was weighed and manually loaded into the feeder hopper. Biomass was then metered into the torrefaction reactor through a rotary airlock and a horizontal auger rotating at 0.4 RPM. The exterior of the reactor was heated using band heater and the biomass temperature was monitored at six different points along the reactor section. A stirrer was provided in the reactor to prevent bridging of particles. Biomass samples were torrefied for 30 min at temperatures of 230 and 270 °C. Torrefied biomass exited at the reactor bottom and was removed via a horizontal auger that cooled the material to about 50 °C before it exited through the twin knife-blade air locks. The residence time of the material in the torrefaction reactor can be controlled between 15 min and 1 h by adjusting the speed of the out-feed auger. An inert environment was maintained in the reactor by injecting clean nitrogen gas (heated to the desired torrefaction temperature of 230 and 270 °C) into the sides and bottom of the vertical thermal section. The inert gas, combined with process off-gas exited from the thermal unit at the upper end in a counter flow configuration. The gas was then passed through a heated cyclone separator to remove the particulates and then to a thermal oxidizer to burn the combustibles. After exiting the thermal oxidizer, the gas stream passed through an enlarged knockout vessel that provided velocity reduction and slight cooling to allow condensable constituents to drop out of the steam for separate collection. The gas was then reheated prior to recycling into the reactor. The cooled torrefied material collected was stored in air tight barrels.

2.3. Densification

A laboratory-scale flat-die pellet mill (model ECO-10, Colorado Mill Equipment) with a 10 HP, 460-volt, 3-phase motor was used for the pelletization (densification). This machine has been designed for research and development applications for testing the pelletability of variety of raw and pretreated biomass. The rated output of this pellet mill was 30–50 kg/h. The pellet mill was equipped with a hopper to hold the biomass and a screw feeder to uniformly feed biomass into the pellet mill. A flexible rectangular heater (Silicon Rubber Heater, Branom Instrument, WA)
and a flexible tape heater (Briskheat Xtremeflex grounded heavy-insulated heating) with J-type thermocouples and controllers (Model 96A-FDAA-00RG, Watlow, USA) were used to maintain a constant temperature of 70 °C in the hopper and feeder, respectively. A variable frequency drive (model Altivar 71, variable-frequency AC motor driver) was used to control the rotational speed of the pellet mill die, and was held at 60 Hz. Further details of the mill can be found in Tumuluru et al. [12].

For pelletization of ground switchgrass, moisture was added to the biomass to increase moisture content to 26% (w.b.), and commercial corn starch, 2% by weight of the original sample, was added as a binder. The biomass, moisture and binder were mixed for 30 min in a ribbon blender (RB 500, Colorado Mill Equipment, Cañon City, CO). The mixed biomass was stored in cold storage, at about 4 °C. For pelleting the torrefied biomass, commercial corn starch and a biobased lubricant (product number CGL8000 with 99% soyseed oil and 1% molybdenum, Green Cold Lubricants LLC, Colorado Springs, CO) were used with quantities of 5% and 2%, respectively, by the weight of the original biomass. Moisture was added to increase the biomass moisture content to 26% (w.b.). The feeding was carried out uniformly at about 10–12 kg/h to ensure that there were no flow irregularities inside the pelletizer. Following the cooling step, pellets were dried in a mechanical oven at 60–65 °C for about 3–4 h to reduce the moisture to safe storage levels of about 5–7% (w.b.).

2.4. Proximate and ultimate analyses, lower heating value, bulk density and Scanning Electron Microscopy (SEM) images

Using a furnace (model 3-550A, Dentsply Prosthetics, PA), moisture, volatile and ash contents were determined following ASAE standard S358.2 (ASABE Standards, 2006), ASTM D3175 and ASTM E1755-01 respectively. The fixed carbon content was determined by subtracting the volatile and ash contents from the total biomass on dry basis. The ultimate analysis of biomass was measured using an elemental analyzer (PerkinElmer 2400 Series II CHNS/O Elemental Analyzer, Shelton, CT) at Kansas State University (Manhattan, KS). Higher Heating Value (HHV) of biomass was measured using an adiabatic Parr 6200 Bomb Calorimeter (model A1290DDEB, Parr Instrument Co., Moline, Ill.). The lower heating value (LHV, d.b.) of raw and pretreated switchgrass was determined using Eq. (1) [34,35].
\[ \text{LHV} = \text{HHV} - 2.44(9H) \]  
where H is hydrogen content of biomass determined through ultimate analysis (\%, d.b.). The bulk density was measured by packing the biomass tightly in a beaker of known weight and volume similar to the procedure described earlier in Sharma et al. [36]. The initial and final weights of the beaker were measured and the bulk density was determined by the ratio of the weight of the biomass to the volume of the beaker.

The SEM (Scanning Electron Microscopy) images of raw and pretreated switchgrass were obtained using a microscope (Quanta 600, FEI, NJ). The dry ground biomass sample was sprinkled on a stub (with a carbon paper attached to it) and the excess sample removed with a brush. Since, the SEM detects only conductive samples, the biomass sample was bombarded with an ionized gas (Argon) forming a gold colored coating on the top. After sputtering of the biomass sample, it was introduced into a vacuum chamber of the SEM and the images were obtained by adjusting the voltage, magnification and the aperture. The quality of the images was improved by adjusting the sharpness and the brightness [37,38].

2.5. Experimental design

A full factorial experimental design was used with two factors: switchgrass pretreatment and gasification temperatures. Five levels of switchgrass pretreatment were no pretreatment (raw switchgrass), torrefaction at 230 °C and 270 °C for 30 min, densification, and combined torrefaction and densification (torrefaction at 270 °C for 30 min followed by densification) and three levels of gasification temperatures were 700, 800 and 900 °C. The experiments were repeated two times.

2.6. Gasification

The gasification experiments were performed in a fixed stainless steel gasifier tube with a diameter of 0.0254 m (1 in) and a length of 0.9 m as shown in Fig. 2. The tube was housed inside a vertical split-hinge tube furnace (model TVS 12/600, Carbolite Inc., WI, USA). A square metal mesh of diameter 0.0254 m (1 in) was weld inside the gasifier tube, 0.125 m from the bottom, to hold the biomass inside the gasifier for gasification. Two inlets were available at distances of 0.015 and 0.025 m from the gasifier top for injecting nitrogen (to maintain inert atmosphere before gasification) and air (gasification agent) into the gasifier tube. The nitrogen and air flow rates were adjusted using calibrated rotameters.

An air tight cylindrical biomass hopper with diameter of 0.0508 m and length of 0.15 m with a tapered bottom was used to store the biomass above the gasifier tube. A ball valve (McMaster-Carr, Atlanta, GA) below the hopper was used to control the biomass flow into the gasifier. A char box, a thermocouple (K-type) and a gas outlet were connected at the bottom of gasifier. The syngas was collected in gas bags (Tedlar, VWR International, Radnor, PA) at the gas outlet. The gasification temperature was monitored and recorded from the control panel display of the vertical tube furnace and the exit gas temperature was recorded using a Lab VIEW system (National Instruments, Austin, TX). The gases obtained were analyzed using a gas chromatograph (model CP3800, Varian Inc., CA) with a packed column (HayeSep DB-100/120, Alltech Associates, Inc., Deefield, Ill.) and a thermal conductivity detector (TCD).

Two grams of biomass was loaded into the gasifier hopper. Biomass was fed after gasifier temperature stabilized at the set point temperature. Purging gas was switched from nitrogen to air at the flow rate of 2 L/min. Gas samples were collected for 2 min. The 2 min was selected based on preliminary experiments that showed that CO concentration reached below 0.1% after 2 min.

3. Measurements and calculations

The gasification performance was evaluated based on yield and LHV of syngas, and gasifier efficiencies such as carbon conversion and cold gas efficiencies. The total syngas yield was calculated using Eq. (2) [36].

\[ Y_{\text{syngas}} = \frac{(Q_{\text{air}} \times 79)}{(N_2 \times m_b)} \]  
where \( Y_{\text{syngas}} \) is the total syngas yield per kg of biomass, N m\(^3\) kg\(^{-1}\) (d.b.), \( Q_{\text{air}} \) is the flow rate of air, N m\(^3\) h\(^{-1}\), \( N_2 \) is the concentration of nitrogen in the syngas, \% v/v, and \( m_b \) is biomass flow rate (d.b.), kg h\(^{-1}\).

The lower heating value, \( \text{LHV}_{\text{syngas}} \) (MJ m\(^{-3}\)) of dry syngas was calculated using Eq. (3) [23].

\[ \text{LHV}_{\text{syngas}} = \left( \text{HHV}_{\text{biomass}} \times Y_{\text{syngas}} \right) \times \left( \frac{4.2}{1000} \right) \]  
where H\(_2\), CO, CH\(_4\), C\(_2\)H\(_2\), C\(_2\)H\(_4\) and C\(_2\)H\(_6\) are the concentrations (% v/v) of H\(_2\), CO, CH\(_4\), C\(_2\)H\(_2\), C\(_2\)H\(_4\) and C\(_2\)H\(_6\) respectively, in the syngas.

The yield of each syngas component was calculated as the product of concentration and density of each syngas component, and the total syngas yield. Carbon conversion efficiency (CCE) (%) was the percentage of biomass carbon that converted into syngas carbon. Cold gas efficiency (CGE, %) was calculated using Eq. (4) [19].

\[ \text{CGE} = \frac{\text{LHV}_{\text{syngas}} \times Y_{\text{syngas}}}{\text{LHV}_{\text{biomass}}} \times 100 \]
where $LHV_{\text{biomass}}$ is the lower heating value of biomass, MJ kg$^{-1}$.

SAS analysis of variance (ANOVA) and Duncan multiple range tests were used at the 0.05 level of statistical significance (alpha) to analyze the effects of pretreatment and gasification temperature on the individual and total gas yields, syngas LHV, gasifier efficiencies, and bulk density of switchgrass.

4. Results and discussion

The effects of pretreatment on all feedstock characteristics (proximate and ultimate analyses, HHV and bulk density) were significant. Effects of pretreatment and gasifier temperature were also significant on the gasifier performance. However interaction between effects of pretreatment and gasification temperature on gasifier performance was not significant. The details are explained below.

4.1. Effects of pretreatment on properties of switchgrass

Table 1 shows the effects of pretreatment on proximate analysis, and HHV of switchgrass. As expected, moisture contents of switchgrass torrefied at 230 and 270 °C were lower than that of the raw switchgrass because torrefaction, a thermal treatment, results in removal of water and hydroxyl (OH) groups from biomass. However, moisture content of pellets (switchgrass with densification and combined pretreatments) were not analyzed because pellets were dried after densification to safely store the pellets. The switchgrass volatile content significantly decreased with the torrefaction and with the increase in torrefaction temperature from 230 °C to 270 °C due to the partial decomposition of biomass polymers (cellulose, hemicellulose and lignin) and release of lighter volatiles [6]. Higher torrefaction temperature leads to release of even more volatiles. On the other hand, densification did not significantly affect switchgrass volatile content. However, when torrefaction was followed by densification, the resulted switchgrass had the least volatile content (62.63 wt.%). Ash content of switchgrass was affected significantly only by the torrefaction at 270 °C and combined torrefaction and densification pretreatments. The low volatile contents of switchgrass pretreated with torrefaction at 270 °C and combined torrefaction and densification may have resulted in high ash contents. Fixed carbon content was significantly affected by all pretreatments except densification. The fixed carbon content was the highest for switchgrass pretreated with combined torrefaction and densification (31.45 wt.%), followed by that for switchgrass pretreated with torrefaction at 270 and 230 °C.

The HHV of switchgrass was significantly affected by all pretreatments. The HHV was the highest for switchgrass pretreated with torrefaction at 270 °C (27.11 MJ kg$^{-1}$) followed by that for switchgrass pretreated with torrefaction at 230 °C and combined torrefaction and densification pretreatments (Table 1). The increase in HHV could be due to low oxygen to carbon (O/C) and hydrogen to carbon (H/C) ratios in the switchgrass pretreated with torrefaction. Switchgrass torrefied at 270 °C had the lowest O/C ratio of 0.58 and H/C ratio of 0.08 (Fig. 3).

The bulk density of switchgrass was significantly affected ($p < 0.05$) by all pretreatments. The bulk density was the highest for switchgrass pretreated with combined torrefaction and densification (Table 1) followed by those for densified switchgrass, switchgrass torrefied at 270 °C, switchgrass torrefied at 230 °C and raw switchgrass. Bergman and Kiel [14] also reported that bulk density of wood pellets pretreated with combined torrefaction and densification was the highest (850 kg m$^{-3}$) followed by those pretreated with densification (650 kg m$^{-3}$) and torrefaction (230 kg m$^{-3}$). Higher bulk density of combined torrefied and densified switchgrass would make the biomass easier to store and transport as compared to densified, torrefied and raw switchgrass. However, the bulk densities for densified, and combined torrefied and densified switchgrass were lower than those reported in Bergman and Kiel [14] because they pelletized the hot torrefied biomass whereas in this study the torrefied biomass was cooled before pelletization.

Unlike raw and densified switchgrass that showed no openings or pores in its structure (Fig. 4a), torrefied switchgrass showed pores, cracks and fissures (Fig. 4b and c). With an increase in the torrefaction temperature from 230 to 270 °C, number of openings or pores increased (Fig. 4b and c). SEM images obtained for torrefied biomass were similar to the ones obtained by Cheng et al. [39], Ibrahim et al. [40] and Phanphanich [41]. Densification, however, did not result in development of pores (Fig. 4d). Similar SEM images were obtained by Kaliyan and Morey [42] and Stelte et al. [43]. Unlike raw switchgrass that showed prominent fibrous structures, switchgrass with the combined pretreatments of torrefaction and densification showed severely disintegrated fibrous structure due to severe pretreatment first by torrefaction at 270 °C and then by densification with binder (corn starch and a bio-based lubricant) (Fig. 4e). Similar SEM images of effects of combined torrefaction and densification on pine were reported by Reza et al. [44].

4.2. Effects of pretreatment and gasification temperature on $H_2$ and CO yields

Pretreatment and gasification temperature significantly affected $H_2$ and CO yields. Among all pretreatments, gasification of combined torrefied and densified switchgrass resulted in the highest $H_2$ (0.03 kg/kg biomass) and CO (0.72 kg/kg biomass) yields at the gasification temperature of 900 °C and switchgrass torrefied at 270 °C resulted in the lowest $H_2$ (0.005 kg/kg biomass) and CO (0.09 kg/kg biomass) yields at the gasification temperature of 700 °C. At all gasification temperatures, the $H_2$ and CO yields were observed in the following order: combined torrefied and densified switchgrass > densified switchgrass > raw switchgrass > switchgrass torrefied at 230 °C > switchgrass torrefied at 270 °C (Table 2). The $H_2$ and CO yields from the torrefied (only) switchgrass were lower than those from raw switchgrass (Table 2) because oxygen-containing volatiles such as CO and CO$_2$ are released during torrefaction [31,45-48]. Also, $H_2$ and CO yields from switchgrass torrefied at 270 °C was lower (0.22 kg/kg biomass) than those from

<table>
<thead>
<tr>
<th>Pretreatment</th>
<th>Moisture (wt.%)$^a$</th>
<th>Volatile (wt.%)$^a$</th>
<th>Ash (wt.%)$^a$</th>
<th>Fixed carbon (wt.%)$^a$</th>
<th>HHV (MJ kg$^{-1}$)$^*$</th>
<th>Bulk density (kg m$^{-3}$)$^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>No pretreatment</td>
<td>9.80 (0.65)$^a$</td>
<td>80.63 (0.18)</td>
<td>5.05 (0.44)</td>
<td>15.87 (0.42)</td>
<td>20.60 (0.69)</td>
<td>138.33 (4.93)</td>
</tr>
<tr>
<td>Torrefaction at 230 °C</td>
<td>2.39 (0.61)</td>
<td>75.99 (0.54)</td>
<td>20.59 (0.15)</td>
<td>17.38 (0.45)</td>
<td>23.53 (0.19)</td>
<td>166.79 (16.79)</td>
</tr>
<tr>
<td>Torrefaction at 270 °C</td>
<td>2.03 (1.04)</td>
<td>67.52 (0.93)</td>
<td>3.98 (0.50)</td>
<td>27.51 (1.38)</td>
<td>27.11 (0.27)</td>
<td>186.78 (16.45)</td>
</tr>
<tr>
<td>Densification</td>
<td>5.05 (0.78)</td>
<td>80.23 (0.54)</td>
<td>3.62 (0.14)</td>
<td>16.15 (0.67)</td>
<td>19.14 (0.25)</td>
<td>498.63 (6.76)</td>
</tr>
<tr>
<td>Torrefaction at 270 °C and densification</td>
<td>7.44 (0.15)</td>
<td>62.63 (0.23)</td>
<td>5.91 (0.16)</td>
<td>31.45 (0.38)</td>
<td>22.27 (0.32)</td>
<td>598.17 (3.09)</td>
</tr>
</tbody>
</table>

$^a$ Means with the same letters under the same column are not significantly different at 5% level.

$^*$ Numbers in parentheses are standard deviation ($n = 3$).
switchgrass torrefied at 230 °C (0.3 kg/kg biomass) possibly due to release of more volatiles during torrefaction at higher (270 °C) temperature. In spite of the lowest volatile content (Table 2) of combined torrefied and densified switchgrass, gasification of this biomass resulted in the highest CO yield (Table 3). This implies that use of binder and moisture during densification might have aided in improving biomass properties.

As expected, the H₂ and CO yields also increased with an increase in gasification temperature from 700 to 900 °C for all switchgrass (Table 3). The trend of increasing H₂ and CO yields with increasing gasification temperature was consistent with results reported by Mom and Sulaiman [49], Gao et al. [50], Patel [27] and Umeki [51] for other types of biomass. Increases in H₂ and CO yields with increase in gasification temperatures can be

![Van Krevelen diagram comparing charcoal with raw and pretreated switchgrass.](image)

**Fig. 3.** Van Krevelen diagram comparing charcoal [6] with raw and pretreated switchgrass.

![Scanning Electron Microscopy (SEM) images of switchgrass.](image)

**Fig. 4.** Scanning Electron Microscopy (SEM) images of (a) raw switchgrass, (b) switchgrass torrefied at 230 °C, (c) switchgrass torrefied at 270 °C, (d) densified switchgrass, and (e) combined torrefied and densified switchgrass.
and CO yields of switchgrass torrefied at 270°C, whereas combined torrefied and densified switchgrass resulted in the lowest CH$_4$ yield can be arranged in the following order: combined torrefied and densified switchgrass > densified switchgrass > raw switchgrass > switchgrass torrefied at 230°C > switchgrass torrefied at 270°C. 

4.4 Effects of pretreatment and gasification temperature on syngas LHV

Effects of pretreatment and gasification temperature on CH$_4$ yield were significant ($p < 0.05$). Switchgrass torrefied at 270°C resulted in the highest CH$_4$ yield (0.12 kg/kg biomass) at the lowest gasification temperature of 700°C, whereas combined torrefied and densified switchgrass resulted in the lowest CH$_4$ yield (0.05 kg/kg biomass) at the highest gasifier temperature of 900°C. This trend was contrary to the trend of CO and H$_2$ yields. At all gasification temperatures, CH$_4$ yield can be arranged in the following order: combined torrefied and densified switchgrass < densified switchgrass < raw switchgrass < switchgrass torrefied at 230°C < switchgrass torrefied at 270°C (Table 2). CH$_4$ yield decreased with an increase in gasification temperature, for all switchgrass similar to the trends reported by Mom and Sulaiman [49] and Lucas et al. [32]. The highest H$_2$ and CO (main combustible components of syngas) yields of combined torrefied and densified switchgrass resulted in the highest syngas LHV at the gasification temperature of 900°C. Similarly, the lowest H$_2$ and CO yields of switchgrass torrefied at 270°C resulted in the lowest syngas LHV at the gasification temperature of 700°C.

4.5 Effects of pretreatment and gasification temperature on gasifier efficiencies (carbon conversion efficiency, CCE, and cold gas efficiency, CGE)

CCE and CGE were significantly affected ($p < 0.05$) by pretreatment and gasification temperature. Among all switchgrass pre-treatments, combined torrefaction and densification resulted in the highest CCE (92.53%) and CGE (68.40%) at the gasification temperature of 900°C due to the highest H$_2$ and CO yields, whereas, torrefaction of switchgrass at 270°C resulted in the lowest CCE (56.06%) and CGE (31.79%) at the gasification temperature of 700°C due to the lowest H$_2$ and CO yields. The low gasification efficiencies (CCE and CGE) of torrefied switchgrass can be attributed to the loss of volatiles released during torrefaction. At all gasification temperatures, CCE and CGE can be arranged in the following order: combined torrefied and densified switchgrass > densified switchgrass > raw switchgrass > switchgrass torrefied at 230°C > switchgrass torrefied at 270°C (Table 2). CCE and CGE also increased with an increase in the gasification temperature (Table 3) for all switchgrass pretreatments.

5. Conclusions

The effects of switchgrass pretreatment and gasification temperature on the gasification performance were evaluated. Gasification temperature and pretreatment had significant effects on gas yields, syngas LHV and gasifier efficiencies (CCE and CGE). With an increase in the gasification temperature from 700 to 900°C,
the H\textsubscript{2} and CO yields, syngas LHV, and gasifier efficiencies increased but the CH\textsubscript{4}, CO\textsubscript{2}, and N\textsubscript{2} yields decreased. Among switchgrass pretreatments, gasification performance of switchgrass with combined torrefaction and densification was the best followed by that of densified, raw, and torrefied switchgrass. The gasification of combined torrefied and densified switchgrass resulted in the highest yields of H\textsubscript{2} (0.03 kg/kg biomass) and CO (0.72 kg/kg biomass), highest syngas LHV (5.08 MJ m\textsuperscript{-3}), CCE (92.53%), and CGE (68.40%) at the gasification temperature of 900 °C. Gasification of switchgrass torrefied at 270 °C resulted in the lowest yields of H\textsubscript{2} (0.005 kg/kg biomass) and CO (0.09 kg/kg biomass), lowest syngas LHV (3.71 MJ m\textsuperscript{-3}), CCE (56.06%), and CGE (31.79%) at the gasification temperature of 700 °C.

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