

Case Study

Comparative analysis of slow pyrolysis of sugarcane bagasse and corn stover for renewable energy production

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Received: 22 September 2024 / Accepted: 2 December 2024

Published online: 05 December 2024

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Abstract

This study presents a comparative analysis of slow pyrolysis applied to sugarcane bagasse from the Kenana Factory in Sudan and corn stover, focusing on biofuel production potential. Experiments were conducted with a heating rate of 0.9 °C/s, raising temperatures from 255 °C to 686 °C over a 50-min residence time. The results show that corn stover achieved a higher bio-oil yield (5.3%) than bagasse (4.26%) and a combined mixture (6.3%). Biochar yields were highest for the bagasse-corn stover mixture at 64.4%. Notably, the calorific value of biochar from corn stover reached 40.8 MJ/kg compared to 38.8 MJ/kg for bagasse, indicating its greater potential for energy applications. These findings underscore the suitability of Sudanese agricultural residues for renewable energy, with corn stover emerging as a favorable bio-oil and biochar source.

Keywords Slow pyrolysis · Bio-oil · Bio char · Sugarcane bagasse · Corn stover · Biomass conversion · Biofuel production and calorific value

1 Introduction

Energy is fundamental to human existence, playing a crucial role in nearly every activity. Throughout each day, energy is constantly utilized. In early times, humans relied on muscle power, fire, and animal power. Eventually, they learned to harness and convert energy into useful forms for various applications. There are mainly three energy sources: conventional, renewable, and alternative energy such as nuclear energy [1, 2]. The fossil energy sources are coal, natural gas and petroleum. The renewable energy sources covered are solar, wind, bioenergy, hydropower and geothermal. Now a day the fossil fuels represent more than 80% of the world energy consumption [1, 3–5]. In the combustion process of these fuels (coal, oil and natural gas), a reaction between it and the oxidizer occurs to release heat (thermal energy) and emit the pollutant emissions. Current researchers aim to enhance combustion performance and minimize pollutant emissions. They are several ways to reduce the pollutant emissions such as use the renewable energies. In the current moment biomass play an important way in the energy around the world. Biomass fuel is becoming increasingly attractive as a substitute for conventional energy sources like fossil fuels due to the growing demand for clean energy. Also the declining fuel reserves and its contribution towards reducing dependence on fossil fuels such as coal and crude oil [1, 6, 7]. They are many way to used biomass as the fuels. Thermochemical and biochemical are the main method to process

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biomass or energy generation [8, 9]. Pyrolysis, gasification, and direct combustion are the most common thermochemical methods for converting biomass. Among these, combustion is the most widely used due to its lower cost and ease of converting biomass into heat energy compared to other methods [8, 10–12]. With increasing energy demand and environmental concerns, this study examines biomass, particularly sugarcane bagasse and sawdust, as a cleaner alternative to fossil fuels. Slow pyrolysis of these materials yields bio-oil with a high calorific value, indicating reduced emissions and promising uses in transportation and industrial applications [13]. Haitao Lin et al. [14] evaluate four biorefinery pathways for corn stover—biohydrogen, biomethane, and bioethanol—by examining their kinetics, emissions, and economic viability to support large-scale application decisions. The results indicate that the BMP pathway yields the highest energy output, while the PFBHP pathway offers significant economic benefits. Additionally, both the PFBHP and DFBHP pathways produce no greenhouse gas emissions. The gasification of biomass is generally a complex thermochemical, this process converts biomass into a gaseous product at high temperatures (900–1200 °C). It uses gasification agents such as air, oxygen, steam, or their combinations in a sub-stoichiometric environment, maintaining an equivalence ratio (ER) of 0.2–0.4 (air-to-fuel ratio = 1.5:1 to 1.8:1), to produce a gas mixture known as syngas or producer gas [15–18]. The pyrolysis technique is one of the thermochemical methods that use to convert biomass to heat. Low-density biomass is thermochemically decomposed at high temperatures without an oxidizer (oxygen), converting it into high-density bio-oil, biochar, and non-condensable gases (NCG). These pyrolysis products have various applications: biochar can be used as an adsorbent, NCG can be converted into flue gases for reactor energy, and bio-oil can serve as a transportation fuel [11, 19–22]. Pyrolysis can be classified into three main categories based on operating conditions: slow, fast, and flash pyrolysis. These categories vary in terms of heating rate, temperature, biomass particle size, solid residence time, and other factors [23]. Slow pyrolysis, also known as conventional pyrolysis, involves the thermal decomposition of biomass in a low oxygen environment, or with significantly less oxygen than required for combustion. Optimal yield and char quality depend on specific parameters: a reaction temperature typically between 400 and 500 °C for most biomasses, a slow heating rate (1–50 °C/min), using large biomass particle sizes generally less than 5 cm, and ensuring a long vapor residence time (5–30 min) to enhance secondary reactions [1, 24]. In slow pyrolysis, the longer residence time allows for continued vapor reactions and secondary cracking, reducing organic liquid yield while increasing char and gas production. The slow heating rate and large biomass particle size create a temperature gradient within the particle, effectively lowering the internal pyrolysis temperature. This promotes dehydration and secondary reactions, enhancing char yield. As carbonization progresses, the thickening char zone decreases thermal conductivity and increases heat transfer resistance. This gradient intensifies over time, making inner zone heating more challenging. Typically, slow pyrolysis yields approximately 35% char, 30% liquid, and 35% gas [25, 26].

Sugarcane bagasse is the one types of biomass. It has been used from the early time since the sixth century Before Christ (BC) in the Pacific Ocean. Next to that, it was disseminated all over the hold world, for different applications such as nutrition and construction fields [27]. Today, Americas production around 51.7% of the worldwide sugarcane s attributed to the, followed by Asia (41.6%), Africa (5%), and Oceania (1.7%) [27].

Bagasse is a residue abundantly produced in the agro-industry, primarily from sugarcane. It consists of fibrous remnants left after cane stalks are crushed for juice extraction. Bagasse typically exhibits colors ranging from gray-yellow to pale green and varies significantly in particle size. This underutilized renewable material comprises two main cellular components: a robust, long-fibered fraction from the rind and fibro-vascular bundles, and a pith fraction from the ground tissue's thin-walled cells. For every wet ton of sugarcane processed, approximately 100 kg of sugar, 35 kg of molasses, and 270 kg of wet bagasse are produced [25, 27–30].

Research has explored both fast and slow pyrolysis of sugarcane bagasse, focusing on pyrolysis parameters and characterizing the resulting products such as biochar [31], bio-oil [32], and gas [33]. Around 23–28% charcoal was produced from bagasse using a two-stage slow pyrolysis method: the first stage involved drying and heating to 350 °C, followed by a second stage at 475–500 °C for the glowing phase [34]. Karaosmanoglu et al. investigated the impact of different heating rates (10 and 30 °C/min) and found that higher heating rates increased liquid production, while lower heating rates favored char formation [35]. To improve the char it was used pellet production of bagasse in slow pyrolysis by increasing the size of the biomass particles [36]. Higher density pellets of bagasse were found to yield more char and exhibit less shrinkage during slow pyrolysis. However, pellet production is a costly pretreatment that can enhance pyrolysis char yields [36]. The slow pyrolysis of sugarcane bagasse was tested in a fixed-bed reactor by Asadullah et al. the rate of heating it was around 0.9 °C/s. Due this slow of rate of heating slightly increased char yield. For cooling there were used two condensers, the first at 60 °C and the second at – 5 °C. It was found that the optimal liquid yield was 66 wt% bio-oil at 490 °C [37]. Energy cane, a sugarcane type with high fiber and low sucrose content, is ideal for bioenergy production on low-fertility soils without competing with food crops. This study examined the pyrolysis of energy cane

bagasse, revealing that reaction temperature greatly influences product composition. Activation energies for different biomass components were identified, highlighting the potential of energy cane bagasse for biofuel over conventional combustion [38]. Colombia's sugarcane industry produces both industrial residues, like bagasse, repurposed for energy, and agricultural residues often left in fields. This study found that agricultural residues have higher ash content and lower combustion reactivity than industrial residues. Thermogravimetric analysis showed that industrial residues are more stable and better suited for energy applications [39].

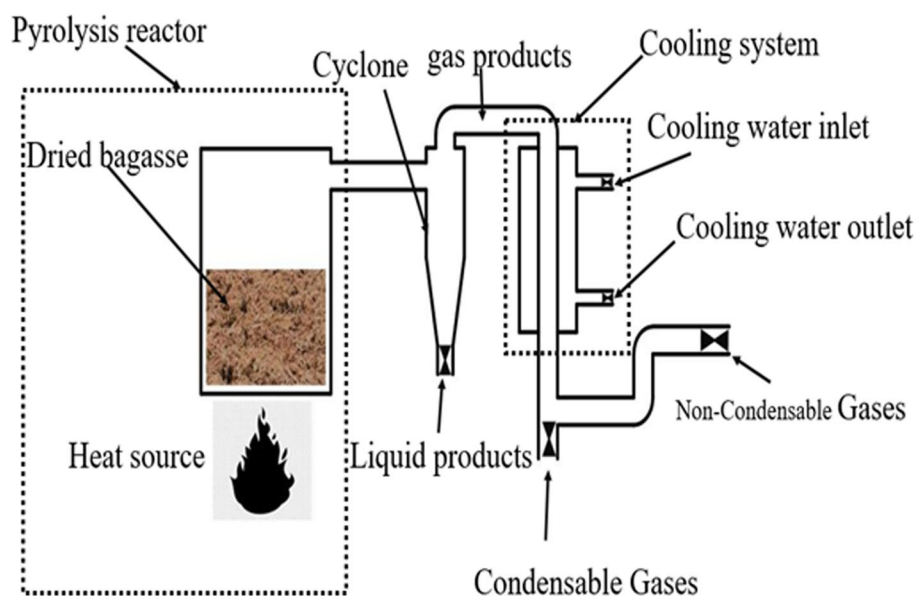
Sudan has a large land this land use for grows different types of crops such as corn. The waste of the corn stover is the residue that is left on the soil surface after corn grain mowed. It was found that the corn stover have higher energy content [40]. It was found the calorific value of 16.5 MJ/kg by A. S. Bennett, et al. [41]. In addition it was recorded calorific values of the corn stover in range between 16.4 and 17.4 MJ/kg [42]. The compositions of the corn stover was showed that corn stover had a high natural ash content (5.1%) compared to wood (0.5% to 1.7%) this studies was reported by Demirbas [43]. It was found that the bio oil from the corn stover produced from microwave pyrolysis showed very low UHV value of 2.65 MJ/kg. T at due to presence of large proportions of phenolic compounds [44]. It was found that the HHV of corn stove was 16.71 Mg/kg [45].

This research uniquely examines Sudanese agricultural residues, specifically sugarcane bagasse from the Kenana factory and corn stover, providing valuable insights for Sudan's renewable energy needs—a focus rarely addressed in existing studies. By conducting a comparative analysis of these two types of biomass under slow pyrolysis conditions, the study contributes a direct comparison not commonly found in literature, potentially identifying the more efficient feedstock for renewable. The objective of this work to analysis of sugarcane bagasse from Kenana factory and corn stover in Sudan.

2 Methodology and experimental setup

Figure 1 shows the pyrolysis system used in this experimental work. The main components of the test rig include the pyrolysis reactor, cooling system, cyclone separator, and connecting pipes. The pyrolysis reactor is where the bagasse and corn stover particles are placed for burning. Volatile particles exit the reactor through a tube connected to its upper part. The reactor, made of stainless steel for its high thermal resistance, has an outer diameter of 29.1 cm, a thickness of 8 mm, and a height of 40 cm. A cyclone separator is used to separate particles from the gas. The cooling system cleans the syngas by condensing gases, using a double pipe heat exchanger with an inner diameter of 5 cm, an outer diameter of 10 cm, and a height of 45 cm. Hot gases from the reactor pass through the cyclone separator and then through the inside of a smaller tube. Cooling water flows in the space between the two tubes to condense the condensable gases, allowing the non-condensable gases to continue flowing. Steel pipes, which can withstand high temperatures, are used

Fig. 1 Lab-scale pyrolysis for this study [46]



to transfer gases through the system. The pipes have diameters of 1 to 2 inches, with lengths of 15 cm from the reactor to the cyclone and 50 cm from the cyclone to the cooling system.

2.1 Experimental method

Samples preparation of sugarcane bagasse and corn stover for this study. Sugarcane bagasse, one of the most abundant biomass resources in Sudan, was supplied by Kenana factories with a high moisture content of 50–52% [46]. In addition, the sample of corn stover was supplied from North of Khartoum. The samples of the sugarcane bagasse was dried by direct under atmospheric air and sunlight in Khartoum State about ten days to reduce the moisture content (5–15) %. For this work the slow pyrolysis process was chosen. Slow pyrolysis was carried out in a locally prepared system at an external workshop and then brought to the university campus. In a typical experiment, a briquette made from sugarcane bagasse and corn stover was placed in the reactor at room temperature (40 °C). After sealing the reactor to prevent air entry, heating was initiated. The following experimental steps were conducted:

1. 750 g of sugarcane bagasse and same this mass was loaded into the reactor.
2. When filling the sugar cane bagasse, the reactor was fully closed, and the heating system was turned on.
3. The temperature started to increase with time; the vapor was beginning to evaporate after a few minutes.
4. The total time required for the first experiment was 50min.
5. After 50 min, the reactor's outside temperature was measured by putting a thermocouple type-K at the top of the reactor cover.
6. A gas analyzer sensor has been located on the gas outlet, and four (4) results were recorded in intervals of 5min each for four times (20 min), taking into account that the syngas outlet was closed after each reading.
7. Samples were taken from the produced tar and bio-oil and were sent to an outside laboratory. The experiment was carried out twice for the two samples of bagasse, the first is the sample Kenana bagasse of and the second is the sample of corn stover. All the experimental was Carry out at the same conditions.

2.1.1 Temperature control and monitoring

Thermocouples: Type-K thermocouples are used to monitor the temperature at critical points of the pyrolysis reactor. One thermocouple is positioned on the reactor cover, at the top, to measure the external temperature after each experiment. These thermocouples are regularly calibrated to ensure accurate temperature readings, especially during the heating phase.

Heating System: The heating system is manually controlled to gradually increase the temperature, allowing for a controlled pyrolysis environment. The heating was initiated at room temperature (40 °C) and maintained throughout the experiment for a total duration of 50 min, with a slow, steady increase.

The Table 1 illustrates the steady rise in average temperature during the pyrolysis process over 50 min. Starting at 255 °C in the initial 10 min, the temperature increases gradually to 310 °C by the 20-min mark, reaching 411 °C at 30 min, and further climbing to 527 °C at 40 min. By the final interval of 40–50 min, the temperature peaks at 686 °C, suggesting the culmination of the heating phase. This consistent temperature escalation indicates a well-controlled slow pyrolysis, achieving optimal conditions for effective biomass decomposition.

Table 1 Temperatures distributions

NO	Time(min)	Average temp (°C)
1	0–10	255
2	10–20	310
3	20–30	411
4	30–40	527
5	40–50	686

2.1.2 Gas composition analysis

Gas Analyzer: A gas analyzer sensor is located at the gas outlet to monitor the composition of non-condensable gases released during pyrolysis. Four readings are recorded at 5-minute intervals over a 20-minute period, with the syngas outlet closed after each reading to prevent any loss of gas and ensure accurate measurements.

Sampling Procedure: After each 5-minute interval, the outlet valve is closed to capture the gas for analysis, ensuring consistent readings across multiple time points.

2.1.3 Product sampling and measurement

Tar and Bio-Oil Sampling: Samples of tar and bio-oil are collected from the system and sent to an external laboratory for further analysis, providing detailed compositional data on these pyrolysis products.

Weight Measurements: 750 grams of sugarcane bagasse or corn stover are loaded into the reactor for each experiment. After the pyrolysis process, the produced biochar, tar, and bio-oil are weighed to determine yield, contributing to the assessment of conversion efficiency.

2.1.4 Process steps and controls

Sealing and Air Exclusion: After placing the biomass in the reactor, the system is sealed to prevent air entry, ensuring an oxygen-limited environment that is essential for slow pyrolysis. This helps prevent combustion and maintains the conditions necessary for pyrolysis.

Time Management: Each experiment is carefully timed, with the process running for a total of 50 min, from initial heating to sample collection, to maintain consistency across experiments.

2.1.5 Experimental consistency and repeatability

Replicated Experiments: The experiment is repeated under the same conditions for two samples, sugarcane bagasse from Kenana and corn stover, to ensure that the results are comparable and that any observed differences are due to the biomass type, not variations in the experimental setup.

2.1.6 Cooling system and condensation process

Condensation Setup: The cooling system uses a double pipe heat exchanger to condense the condensable gases. The cooling water flows through the outer tube, while the hot gases flow inside a smaller, inner tube. This design ensures effective condensation of bio-oil and tar, which can then be collected and analyzed.

These additions to the methodology provide a comprehensive description of the process control and data measurement tools used, along with their placement, calibration, and role in ensuring accurate and reliable results

3 Results and discussions

3.1 Physical analysis of bio-oil and bio char

From the experimental results can observe that both sugarcane Leaves and corn Stover are an abundant, inexpensive and readily available source of lignocellulosic biomass. In addition, the produced liquid oil from the slow pyrolysis of the two samples is divided into two types, bio-oil and tar. The liquid yields were sent to the central laboratory for technical services and calibration to analyze their physical properties. The density of sugarcane bagasse compared to corn stover can be influenced by various factors related to the structure, composition, and growth conditions of the plants. Here are some potential reasons why the density of sugarcane bagasse might be higher than that of corn stover (tables below 2 and 3): Cell Wall Composition: The composition of the plant cell wall, including cellulose, hemicellulose, and lignin, can affect biomass density. Sugarcane bagasse may have a cell wall structure with a higher lignin content, which tends to contribute to higher density. Lignin Content: Lignin is a complex polymer found in plant cell walls that provides structural support. Sugarcane bagasse typically has higher lignin content than corn stover.

Table 2 Sample (sugarcane bagasse) bio-char

No	Test	Test method	Result	Unit
1	Density @15°	ASTMD4052	1.2228	g/m ³
2	Calorific value	Calorific value	38.8	MJ/kg

Table 3 Sample (corn stover) bio-char

No	Test	Test method	Result	Unit
1	Density @15°	ASTMD4052	1.12	g/m ³
2	Calorific value	Calorific value	40.8	MJ/kg

Table 4 Sample of (sugarcane bagasse and corn stover) bio-char

No	Test	Mass (g)	Test method	Result	Unit
1	Density @15°	750g bagasse 750g corn stover	ASTMD4052	1.1418	g/m ³
2	Calorific value	750g bagasse 750g corn stover	Calorific value	40.5	MJ/kg

Table 5 Component percentages from pyrolysis of bagasse, corn stover, and their mixture

Sample	biochar	Bio-oil	Tar	Ga + losses
Bagasse	54.3%	4.26%	14.0%	27.6%
Corn Stover	53.1%	5.3%	16.3%	25.3%
Bagasse + Corn Stover	64.4%	6.3%	15.1%	14.3%

Higher lignin content is associated with increased biomass density. Vascular Bundle Structure: The arrangement and density of vascular bundles within the plant can impact overall biomass density. Sugarcane bagasse may have a more tightly packed or denser vascular bundle structure than corn stover. Genetic Differences: Different plant species or varieties within the same species may exhibit variations in biomass density due to genetic factors.

From Tables 2 and 3 can observe that the density decreased calorific value increased. The calorific value increased whilst the oxygen content decreases, because the pyrolysis process can occur in either the total absence or lean oxidation condition supply. From Table 4 it can investigate also the density decreased calorific value increased for the sample it is mixture between the sugarcane bagasse and corn stover. These results were agreed with previous studies [27, 47–50].

The results are shown in the Tables 2, 3 and 4. It has been seen that the calorific value of the first sample (bagasse) is equal to (38.8 MJ/kg), the calorific value of the second sample (corn stover) is equal to (40.8 MJ/kg). The calorific value for the corn stover it is more than sugarcane bagasse due to the presence of inorganic ash in biomass can affect its calorific value. Higher ash content in sugarcane bagasse, which may contain minerals and inorganic compounds, could contribute to a lower calorific value. In addition, the calorific value is typically reported on a dry basis. If sugarcane bagasse has a higher moisture content than corn stover, it would dilute the energy content on a dry basis, potentially resulting in a lower calorific value. These results align with previous studies on the calorific value of char from bagasse, highlighting its high carbon content and combustibility, which make it a promising biofuel alternative to fossil fuels in industrial applications [27, 51].

3.2 Chemical analysis of bio-oil

In the pyrolysis experiment of sugarcane bagasse, the results included a homogeneous dark brown (semi-black) liquid, a black high-density tar, gas that burns with a blue flame, and dark brown biochar with some undecomposed substances remaining in the reactor after the process. Table 5 shows the percentage of components resulting from the slow pyrolysis of bagasse, corn stover, and a mixture of bagasse and corn stover.

The mass analysis biochar 56.2% bio-oil, 6.14% tar, 8.8% gas loss 28.8%. A homogeneous dark brown (semi-black) liquid, a black high-density tar, gas that burns with a blue flame, and dark brown biochar with some undecomposed substances remaining in the reactor after the slow pyrolysis process are completed. For the mass analysis of corn stover are biochar 53.1%, bio -oil 5.3%, tar 16.3% and gas + losses 25.3%. From this table for biochar it can observe that the moisture content of the biomass can affect the efficiency of pyrolysis and biochar formation. Higher moisture content may require more energy to drive off water, affecting the overall yield of biochar. About the bio oil the ash content in biomass can influence the pyrolysis process. Higher ash content may lead to the formation of inorganic compounds, reducing the yield of bio-oil. The composition of corn stover and sugarcane bagasse, including the types and amounts of cellulose, hemicellulose, lignin, and other organic components, can influence tar formation. Corn stover may have a composition that leads to a higher yield of tar during pyrolysis. For the gas + losses the moisture content of biomass can affect the efficiency of pyrolysis. Higher moisture content may lead to the generation of steam and other gases during the process, contributing to increased gas loss. If sugarcane bagasse has higher moisture content, it could be a factor. Based on Wadah Mohammed Mahdi Omer's [52] analysis, Sudanese bagasse is well-suited for bioenergy production, with 76.6% volatile matter for efficient pyrolysis, low ash content (4.1%) to reduce slagging, 19.3% fixed carbon enhancing energy density, and a moisture content of 6.8%, indicating minimal energy loss in combustion or pyrolysis. This favorable composition and low impurity level underscore its potential for bioenergy applications.

The table analysis shows the yields for biochar, bio-oil, tar, and gas/losses from bagasse, corn stover, and their mixture: biochar (54.3% for bagasse, 53.1% for corn stover, 64.4% for the mixture), bio-oil (4.26%, 5.3%, 6.3%), tar (14.0%, 16.3%, 15.1%), and gas/losses (27.6%, 25.3%, 14.3%), respectively. Each component was evaluated as a percentage of the initial biomass weight, with biochar measured as the solid residue, bio-oil from condensation, tar collected alongside bio-oil or separated by temperature-specific filtration, and gas/losses inferred as the remaining difference. The relatively high tar fraction, unusual for slow pyrolysis, may result from specific biomass composition, operating conditions, or heating rate variations, suggesting that these experimental conditions promoted higher tar yields.

4 Conclusion

Finally the bio-oil acquired from the slow pyrolysis process underwent a thorough physical analysis. It was observed that the calorific values were notably high, surpassing those reported in previous studies conducted in other countries, as detailed in the concluding section of chapter two. This enhanced calorific value could potentially be attributed to the low water content in the bio-oil, as highlighted in the preceding discussion, resulting from lower oxygen levels. The physical analysis further revealed that, among the three samples, corn stover exhibited the highest calorific value.

Author contribution Abuelnuor A. A. Abuelnuor was the main contributor to the research design, experimental setup, data collection, and analysis of bio-oil and biochar results. He was also responsible for drafting the majority of the manuscript and interpreting the experimental data. Mohamed Ali Abuelnour contributed to the development of the research framework, provided guidance during the experimentation process, and assisted in the data analysis. He was responsible for reviewing and refining the manuscript, as well as handling correspondence and finalizing the submission. O. S. Abd El-Kawi provided technical supervision, ensuring the accuracy of the experimental procedures and contributing to the review and editing of the manuscript.

Data availability The datasets generated during and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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