Research article

The effect of feedstock densification on the process and product properties of sugarcane leaves pyrolysis

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Abstract: Sugarcane leaves are the main residue constitute approximately 14% of the total weight of the remaining sugarcane after harvesting. An effective method for processing sugarcane leaves residues is needed at low cost without causing any environmental problem. This research aims to disclose the effect of sugarcane leaves densification method applied prior to pyrolysis process in a pilot scale reactor. To evaluate the process and its product, the experiments were carried out into two types: (*i*) pyrolysis of sugarcane leaves without densification at 320 °C with a variation of pyrolysis time for 100, 120, and 130 minutes and (*ii*) pyrolysis of densified sugarcane leaves with the variation of pyrolysis temperature 320 °C and 420 °C. The investigated conditions showed that the effect of sugarcane leaves densification prolong the pyrolysis time up to 240 minutes at a pyrolysis temperature of 320 °C, and increased the yield of biochar and bio-oil products up to 41% and 38%, respectively. However, in term of the physical properties of biochar products, the fixed carbon content decreased by 7% when the sugarcane leaves were compacted. While other parameters found no significant difference in pyrolysis at 320 °C, the effect of sugarcane leaves densification is very beneficial especially when the pyrolysis was performed at 420 °C.

1. Introduction

Fossil fuels, such as coal, oil, and natural gas, are currently the world's main source of energy and account for more than 80% of the world's energy consumption, resulting in rising prices and declining oil reserves [1]. Therefore, feedstocks other than fossil fuels are needed due to the decreasing oil reserves and increasing energy demand. Lignocellulosic biomass is one of the renewable hydrocarbon sources that can be converted into liquid, solid, and gaseous fuels, as well as heat and energy, without CO_2 emissions [2].

It is clear that two-thirds of sugarcane biomass, a type of lignocellulosic biomass, is not used to produce biofuels, such as ethanol. Only sugarcane juice containing sucrose and glucose is used for ethanol production. While bagasse has not been used to produce biofuels, it has been utilized for bioelectricity. Sugarcane leaves constitute one-third of sugarcane energy that is not utilized in industry. The burning and handling of these leaves has a negative impact on the environment [3].

Indonesia has more than 255,300 hectares of privately owned sugarcane land and about 233,675 hectares of state-owned land. Data from the Directorate of Plantations of the Ministry of Agriculture in 2021 shows sugarcane production reached more than 4.2 tonnes and increased to 36.4 tonnes in 2022. Although sugarcane is a seasonal and productive crop, every tonne of sugarcane harvested produces 140–180 kg of tops and leaves that are not utilized and simply dumped on the land [4]. To prepare the land for the next planting season, the leftover tops and leaves are usually burnt on the land, and there is no proper and effective utilisation of this large amount of residue. This burning also releases CO, CO_2, SO_2 and NO gases that cause land degradation [5].

Pyrolysis is a thermochemical process that causes endothermic biomass degradation in the temperature range of 673–1173 K and produces various products such as biochar, bio-oil and uncondensable gas. As a thermochemical process, pyrolysis requires heat to perform the process economically and consequently kinetic parameters are involved in the reaction. The advantage of pyrolysis technology is that it is a simple and inexpensive technology that can process various kinds of biomass and organic waste. Pyrolysis can reduce the amount of waste discharged into landfills and help minimize environmental pollution and greenhouse gas emissions. The pyrolysis process can produce combustible gas called syngas, which can be used to generate heat and electricity. Pyrolysis can turn solid waste into valuable products such as biochar, which can be used as soil improvement agents to improve soil fertility and carbon sequestration [6].

Most of the biochar production occurs at 250 and 600 °C, which involves exothermic and endothermic processes; dehydration of biomass; breakdown of sugar molecules at low temperatures; removal of volatile substances, and charcoal oxides [7]. Charusiri et al. studied the pyrolysis of sugarcane leaves and observed that the resulting product increased with increasing temperature. At a feed rate of 0.4 kg/h, a pyrolysis temperature of 500 °C, a particle size of 500 μm, and an inert N_2 flow rate of 120 cm^3/min, the highest bio-oil yield was 40.16% [8]. Meanwhile, Conag et al. reported that torrefaction of sugarcane leaves at a temperature of 300 °C for 45 minutes could increase the fixed carbon content from 18% to 21% and the calorific value of 22 MJ/kg [9]. Miranda et al. previously conducted pyrolysis of sugarcane bagasse at a temperature of 650 °C and found that the nitrogen content in biochar was 1.4%. The presence of nitrogen in this biomass is likely related to other

compounds that have low thermal stability. Increasing the pyrolysis temperature will accelerate the evaporation process of volatile compounds, resulting in low nitrogen content [10].

A common strategy to enhance biomass properties is by reducing the moisture content and increase energy density through a densification process. This strategy makes storing, distributing, and utilizing sugarcane leaves easy. Moreover, the densification method is more practical and can reduce overall costs [11], especially for low energy density biomass like sugarcane leaves. So far, there are still limited works have been published on densified biomass pyrolysis. Lack of information can be found in the literature regarding the effect of sugarcane leaves densification on the physical properties and product yields. For this reason, it is important to conduct a pilot-scale study on the impacts caused by the densification method applied before pyrolysis process of sugarcane leaves.

This study aimed to investigate the effect of feedstock densification during the pyrolysis process of sugarcane leaves in a pilot scale apparatus. The objective was to optimize the biochar production through sugarcane leaves densification technique and evaluate the effects on process parameter and product properties. This study also discloses the opportunity of product utilization such as biochar and bio-oil *via* product characterisation procedure. By using densification method of sugarcane leaves, it is expected that the production capacity can be increased and operational costs can be reduced significantly. The results of this investigation are beneficial for establishing an effective method for sugarcane leaves waste management.

2. Materials and methods

2.1. Feedstock preparations

Figure 1 schematically illustrates the stages of the research conducted. Several parameters were measured during the pyrolysis process including reactor temperature profile, fuel consumption, and product yield. The pyrolysis product yield was assessed through proximate analysis, calorific value, and molecular composition of bio-oil.
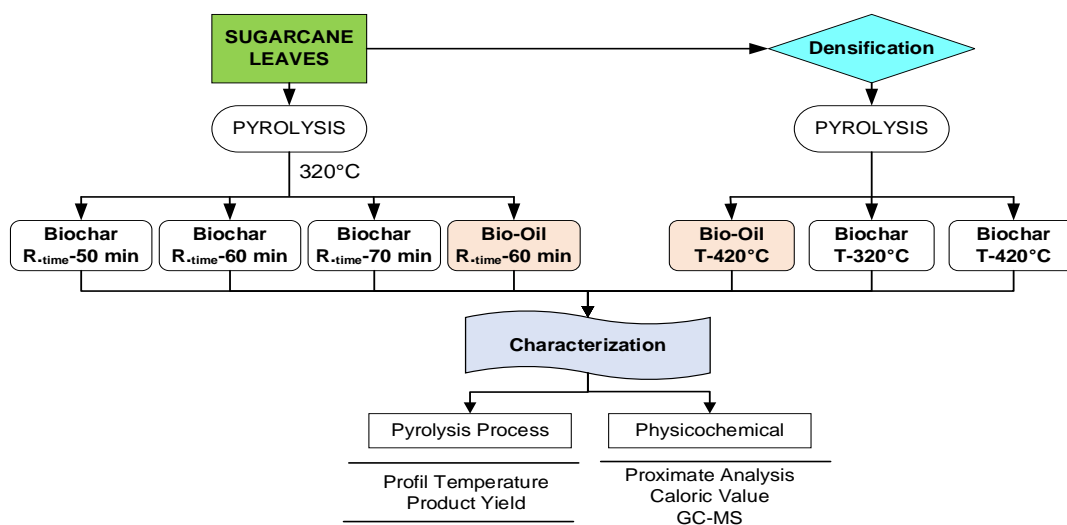

Figure 1. Schematic diagram of the methodology used for biochar and bio-oil production from sugarcane leaves.

2.2. Feedstock densifications

Sugarcane leaves were sourced from a plantation owned by PT Perkebunan Nusantara II, Kwala Madu, Stabat Sumatera Utara. The raw materials were first chopped using a chopping machine and then dried under the sun for three days. The dried sugarcane leaves were then ground and sieved to 40-mesh size. The sugarcane leaves powder was mixed with tapioca starch binder. The ratio between binder and sugarcane leaves powder was 1:5. The mixture of binder and sugarcane leaves powder was then stirred until homogeneous and put into a mold with the shape and size as shown in Figure 2. The densification process was carried out using a hydraulic press at a pressure of 200 kg/cm^2. After the densification process, the sugarcane leaves briquettes were dried under the sun for two days. After drying, the sugarcane leaves briquettes had a diameter of 15 cm and a height of 3 cm with a weight range of 100–110 g.
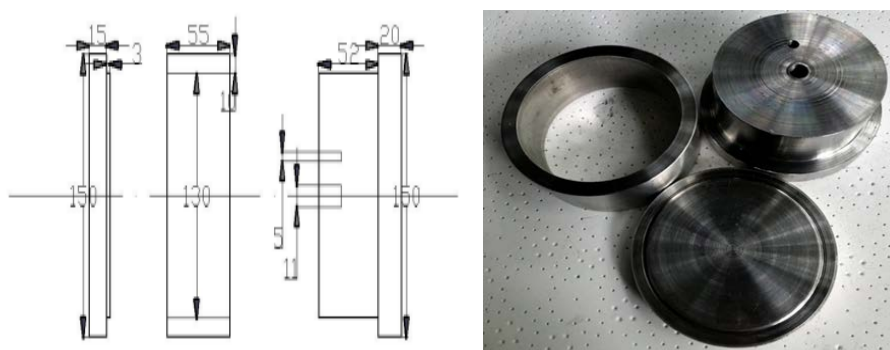

Figure 2. Shape and size of the mold.

2.3. Pyrolysis experiment

Pyrolysis experiments were conducted in a pilot-scale fixed bed type reactor as reported in previous publications [12]. Pyrolysis consists of a 304 stainless steel reactor with a capacity of 30 L. This unit was equipped with a condenser tank with a capacity of 32 L and two separators that function as tar and liquid smoke collectors. The heat energy source was from LPG gas which was fired by a burner located at the bottom of the reactor. The pyrolysis process was carried out by recording the temperature changes in the reactor every minute using a K-type thermocouple sensor. A valve was installed in each separator in order to collect the bio-oil and liquid smoke products after the experiment [13].

In this study, two types of experiments were conducted: (i) sugarcane leaves without densification (SCL) and (ii) sugarcane leaves with densification (DSCL). The SCL process was carried out by feeding about 1.0 kg of dry sugarcane leaves into the pyrolysis reactor and heated to a temperature of 320 °C. After reaching the targeted temperature of pyrolysis at 320 °C, the pyrolysis temperature was held for 100, 120, and 130 minutes. Then, the experiments were named SCL-100, SCL-120, and SCL-130, respectively. Meanwhile, the DSCL process was carried out by feeding the reactor with *ca*. 3 kg of sugarcane leaves which have been densified and then pyrolyzed at temperatures of 320 °C and 420 °C. These experiments were denoted as DSCL-320 and DSCL-420, respectively. Once the desired temperature was reached, the process was held until the thermal decomposition process had completely

finished, which was indicated by no more pressure being built-up in the reactor and no more liquid being produced. The experiment was then stopped by turning off the burner and leaving the reactor to reach room temperature. Next, the reactor was opened to retrieve the biochar and bio-oil. The product yields (i.e., biochar, bio-oil, and uncondensable gas) were calculated using the following Eqs 1–4:

$$Bio - oil\ yield\ (wt\%) = \frac{Bio - oil\ (g)}{Biomass\ feed\ (g)} x100 \tag{1}$$

$$Biochar\ yield\ (wt\%) = \frac{Biochar\ (g)}{Biomass\ feed\ (g)} x100 \tag{2}$$

$$Gas\ yield\ (wt\%) = 100 - \{bio - oil\ yield\ (wt\%) + biochar\ yield\ (wt\%)\} \tag{3}$$

$$Conversion\ (\%) = 100 - \{biochar\ yield(wt\%)\} \tag{4}$$

2.4. Product characterizations

The biochar products were characterized through proximate analysis and bomb calorimeter analysis. Analysis of moisture content, ash, fly matter, and fixed carbon, proximate analysis was carried out following the Indonesian Standard of SNI 06-3730-1995 [14]. Proximate analysis initially was carried out to determine the moisture content. Approximately 1.0 g (W_1) was weighed in a porcelain crucible and placed in an oven at 115 °C ± 5 °C for 3 hours. The crucible containing the dried sample was then transferred to a desiccator and allowed to cool for one hour, and then the sample was weighed (W_2). Moisture content (M) was calculated using Eq 5.

$$Moisture\ content\ (M)(\%) = \frac{W_{1 - w_2}}{W_1} x100 \tag{5}$$

After determining the moisture content, the dried samples in the crucible were analyzed for volatile matter (VM) content by weighing 1–2 g of sample into the crucible (W_1) and then put into the furnace at 950 °C. As soon as the temperature was reached, the crucible was moved into a desiccator for one hour, allowed to cool and then weighed (W_2). Volatile matter (VM) was calculated using Eq 6.

$$Volatile\ matter\ (VM)(\%) = \frac{W_{1 - w_2}}{W_1} x100 \tag{6}$$

To determine the ash content, 2–3 g of sample was weighed and places into the crucible (W_1) and then put it into the furnace at 800–900 °C for 2 hours. After the entire sample became ash, the crucible was removed, put it in a desiccator, allowed to cool, and then weighed (W_2). Ash content was calculated using Eq 7.

$$Ash\ (\%) = \frac{W_1}{W_2} x100 \tag{7}$$

Meanwhile, fixed carbon was determined by difference using Eq 8.

$$Fixed\ carbon\ (FC)(\%) = 100 - M - VM - Ash \qquad (8)$$

The calorific value of the samples was estimated using a bomb calorimeter (Koehler K88990 Bomb-type Calorimeter). The samples were placed in an alumina crucible of approximately 10 mg capacity and then heated from an ambient temperature up to 1000 °C. The molecular composition of the bio-oil was analyzed using a Shimadzu gas chromatography and mass spectrometry instrument equipped with an autosampler (AOC-20S) and autoinjector (AOC-20i). Helium was used as carrier gas.

3. Results and discussion

3.1. Pyrolysis experiment

Pyrolysis was conducted under non densification conditions at 300 °C with sample codes SCL-100, SCL-120, and SCL-130. Pyrolysis time refers to the total time recorded from the start of the heating process until the experiment is terminated. The temperature rise data was recorded every 10 minutes from the beginning to the end of the process, with the temperature rise controlled to stay within the slow pyrolysis zone of below 100 °C, as shown in Figure 3. All three curves show that during the pyrolysis process, the temperature rise occurred consistently and without any significant fluctuations.
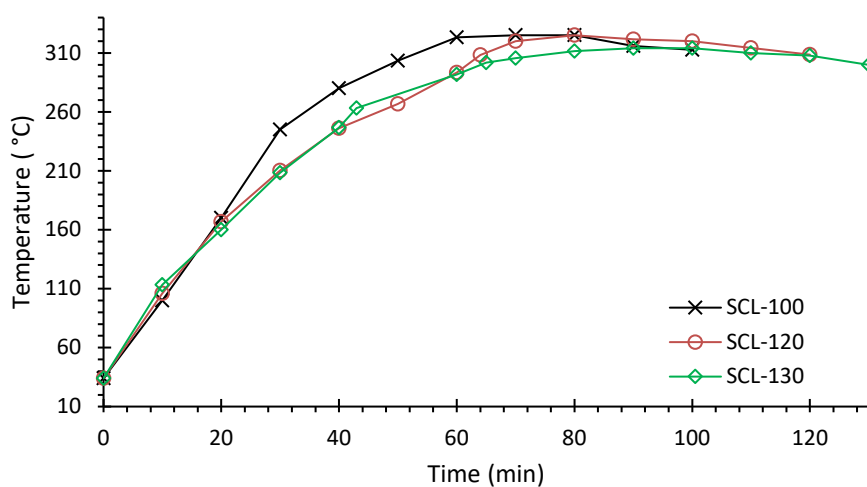

Figure 3. Temperature profiles of SCL pyrolysis.

Based on the data plotted in Figure 3, it is known that the heating rate to reach the maximum temperature for the pyrolysis process ranges between 5–7 °C/min. After reaching the maximum temperature, the residence time was varied to 50, 60, and 70 minutes to determine the effect of residence time on the biochar products produced. These plots are in accordance with the explanation Sun et al. 2017 which stated that the increase in pyrolysis time causes the volatile value and ash content to decrease [15] This is supported with the data summarized in Table 2. Meanwhile, studies on the pyrolysis of bagasse show that increasing the pyrolysis residence time of bagasse can reduce ash content, but after 8 hours, the resulting yield tends to be stable [16]. In this case, the pyrolysis residence

time has little effect on the biochar yield, because when the pyrolysis temperature and residence time increase, the surface structure of the biochar also changes. On the other hand, the LPG fuel requirement to process one kilogram of SCL feedstock increases with the length of pyrolysis time. SCL-100 requires 1.13kg LPG/kg feedstock, SCL-120 1.20kg LPG/kg feedstock, and SCL-130 1.37kg LPG/kg feedstock.

In evaluating the effect of densification at 320 and 420 °C as illustrated in Figure 4, it is observed that the higher the pyrolysis temperature, the time required tends to increase. As obtained at a pyrolysis temperature of 320 °C, it takes about 160 minutes, while to reach a temperature of 420 °C, it takes 240 minutes. It can be concluded that the pyrolysis of densified feedstock requires a longer pyrolysis time compared to those without densification. This is due to the densification effect, that is, the denser the raw material, the longer the pyrolysis time.
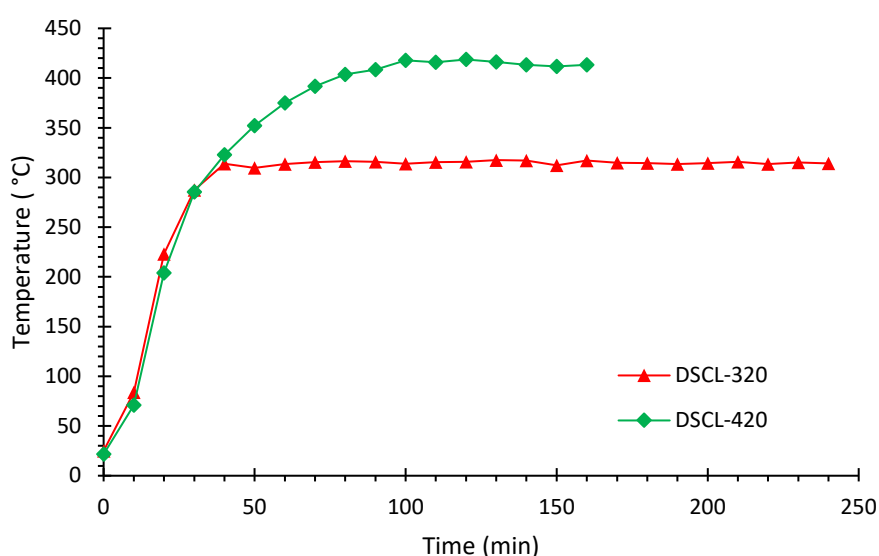

Figure 4. Temperature profile of DSCL pyrolysis.

When the pyrolysis temperature increases, the biomass undergoes decomposition into smaller molecules, so that the resulting biochar product tends to increase along with the increase in temperature [17]. This means that pyrolysis at lower temperatures can increase biochar yield [18]. This explanation is consistent with the results obtained in Table 1, where at a temperature of 420 °C the resulting biochar yield is low compared to DSCL-320 biochar yield. However, as the temperature increases, the calorific value and fixed carbon increase, this is in accordance with the results obtained in Table 2. High process temperature can increase biochar yield, uncondensable gas and calorific value. In addition, increasing the pyrolysis temperature can also improve the deoxygenation process of bio-oil.

In the DSCL sample, the LPG fuel used increased twice as much, when compared to SCL. This is because in the DSCL sample, the sugarcane leaves raw material has undergone compaction at a pressure of 200 kg/cm^2 which results in the sugarcane leaves particles becoming tighter and denser, thus causing the heating (combustion) process to be longer. In addition, the advantage obtained when the sugarcane leaves raw material is compacted, the amount of raw material (DSCL) that enters the pyrolysis reactor is more, than 3 kg when compared to SCL, which is 1 kg. It can be concluded that

the higher the pyrolysis temperature, the LPG fuel used increases, reaching 2.3 kg LPG/kg feedstock in DSCL-320 and 3.13 kg LPG/kg feedstock in DSCL-420.

3.2. Distribution product

The pyrolysis products consist of three products i.e. biochar, bio-oil and uncondensable gas. Biochar is obtained from the pyrolysis reactor, while bio-oil is produced in the form of a mixture of tar and oil, each obtained from separator 1 before passing through the condenser and separator 2 after passing through the condenser. Uncondensable gas is gas that is not analyzed quantitatively and qualitatively. Table 1 shows the yield of products obtained through pyrolysis under the condition of SCL and DSCL.

Table 1. Product yields of SCL and DSCL experiments.

Parameter	Unit	Sample ID				
		SCL-100	SCL-120	SCL-130	DSCL-320	DSCL-420
A. Product Yield						
Biochar	%	32	33	34	41	30
Bio-Oil	%	25	21	21	38	42
Uncondensable gas	%	43	46	45	21	28

Based on the data in Table 1 it can be learnt that the longer the pyrolysis temperature, the more the biochar yield was obtained from SCL experiment. This was shown by SCL-100 which produced 32% biochar, 25% bio-oil, and 43% uncondensable gas. At SCL-120, the biochar and uncondensable gas yields increased to 33% and 46%, respectively, while the bio-oil decreased to 21%. However, the results of DSCL products showed that with the increase of pyrolysis temperature, the biochar yield decreased from 41% at 320 °C to 30% at 420 °C, but the bio-oil and uncondensable gas products increased.

Residence time is generally a temperature-dependent parameter and depends on the reactor design. In general, the longer the residence time, the more the biomass will break down into simpler components. Theoretically, slower pyrolysis and longer residence times produce more biochar. Slow pyrolysis at temperatures (300–400 °C), characterized by a low heating rate (0.1–1 °C/s) and a slow combustion process [19].

During the pyrolysis process, cellulose contained in biomass is converted into volatile substances and lignin forms solid carbon [20]. These results indicate that biomasses with high lignin can produce larger amounts of biochar through pyrolysis [21]. This is in accordance with Zhao L, et al. for mud biochar [22] and Trippe KM, et al. for grass biochar [23]. The results of correlation analysis show that the change in biochar produced from different feedstocks is inversely proportional to their fixed carbon content. Pyrolysis at temperatures below 400 °C can physically remove the adsorbed water fraction and evaporate the aliphatic compounds, which shows a sharp decrease in the devolatilization yield [24]. At pyrolysis temperatures above 400 °C, less volatile substances decompose slowly, while volatile substances are released gradually, forming aromatic and heteroaromatic compounds, which reduces the amount of bio-oil product [25]. This decrease is due to the intensive degradation of biomass, which leads to the formation of uncondensable gases.

Recently, Herrera et al. 2022 studied about biochar production from rice husk using pyrolysis method at temperatures of 450 °C, 500 °C, 550 °C, and 650 °C. It was showed that the process parameters have significant effect on the physicochemical properties of biochar product [26]. By increasing the pyrolysis temperature, the fixed carbon content of resulting biochar was decreased. The content of fixed carbon in all biochar was ranging from 48.65% and 54.59%. Basically, the carbon content increases considerably with respect to the type of feedstock. It was suggested that biomass with higher volatile matter content is undesirable for biochar and bio-oil production.

In term of bio-oil and uncondensable gas products, the higher the pyrolysis temperature, the higher the yield of bio-oil and uncondensable gas. This is consistent with previous results that showed devolatilization of biochar at higher temperatures resulted in greater amounts of liquid and gaseous products. These two results indicate that the amount of feedstock and type of volatile matter formed during pyrolysis at the tested temperature range destroys cellulose, hemicellulose, and lignin compounds [27].

In DSCL sugarcane leaves, the amount of biochar produced decreased with increasing temperature. This is in a good agreement with information published in the literature where at higher pyrolysis temperature, the oxygen content of the biochar is less while fixed carbon content are higher [28]. As shown in Table 2, the yield of un-condensable gas increases with increasing temperature and high heating rate. At high heating rates, the product thermally decomposes and causes rapid condensation, resulting in cracks in which led to the formation of un-condensable products [19].

3.3. Product properties

3.3.1. Characterization of biochar

The physicochemical properties of biochar are shown in Table 2. It can be seen that CSL-100, SCL-120, and SCL-130 biochar products have moisture content, ash content, and volatile biochar content of 3.511%, 24.63%, and 36.13%, respectively. Meanwhile, the moisture content of DSCL increased to 5.85% after densification.

Table 2. Properties of biochar SCL and DSCL.

Parameter	Unit	SCL			DSCL	
		50 min	60 min	70 min	320 °C	420 °C
A. Physical Properties of Biochar						
Caloric value	cal/g	5258	5415	5223	5572	5507
Moisture	%	3.51	2.75	2.05	5.85	3.44
Ash	%	24.63	24.29	23.10	20.04	23.02
Volatile matter	%	36.13	34.36	31.07	43.61	31.23
Fixed carbon	%	37.84	37.19	37.07	30.5	42.31

However, more fixed carbon products were produced in SCL-100 37.83%, SCL-120 37.19%, and SCL-130 37.07%. This is consistent with the statement of [5] that higher solid carbon content indicates better fuel quality.

Upon increasing the pyrolysis temperature of DSCL samples, it was found that the volatile content decreased, as shown in Table 2. The volatile contents of SCL-100, SCL-120, and SCL-130 were 36.13%, 34.36%, and 31.07%, respectively. DSCL-320 and DSCL-420 were 43.61% and 31.23%, respectively. With increasing temperature, the ash content also increased due to the loss of volatile substances in the biomass and the formation of inorganic compounds.

As reported by Maj G [29], the volatile matter content in forest waste ranges from 34%–54% at 300 °C and between 6%–19% at 600 °C. With increasing pyrolysis temperature, the content of water and volatile substances in the feedstock decreased, while the content of ash and solid carbon increased [21]. This is similar to data reported by Yang X, et al. [30], where increasing the pyrolysis temperature of apple branch bio-briquettes can reduce the volatile content by 60.8%–14.9%. This is due to the continuous process of breaking down the volatile fraction into low molecular weight liquids and gases, except for biochar [31]. In addition, an increase in pyrolysis temperature can lead to the contraction of hydroxyl groups and thermal degradation of cellulose and lignin compounds [27]. The biochar processed at low temperature contains hydroxyl carbonyl, carboxyl, and hemiacetal compounds, while the biochar processed at high temperature contains pyronine and ester [32]. Nurazzi et al. 2021 reported that cellulose gradually undergoes chemical changes as the temperature increases [33]. In the first stage of the pyrolysis process, at temperatures up to 250 °C, biochar is dominated by oligosaccharides [7]. At the same time, when the temperature increases to 290 °C, phenolic and furan compounds appear in the biochar. At temperatures above 290 °C, biochar is mostly composed of alkyl furan compounds, benzene aromatic hydrocarbons, and condensed aromatic hydrocarbons. The content of volatile substances in biochar affects the stability of the product [34].

The carbon and ash content of biochar increases with increasing pyrolysis temperature. The high carbon content indicates that the biochar still contains some residual original organic compounds, including cellulose [35]. According to the study by Maj G [29], the ash content rises to 5.7 and 18.7% as the temperature rises. The increase in ash content is due to an increase in the concentration of inorganic components and combustion residues [36]. Furthermore, an increase in Mg, Ca, K, and P in biochar pyrolyzed at high temperatures can increase the ash content by between 4.0 and 33.1% [37]. In addition, increasing the pyrolysis temperature can also increase the carbon content up to 92.4%, this is due to the higher degree of polymerization so that a carbon structure is formed in biochar [38]. As revealed by Erdogan et al., the carbon content of biochar from orange pomace increased with increasing pyrolysis temperature, which was between 56.8 and 68.1% [39].

During the experiment, volatile compounds are released and absorbed through the condensation process, but some residues remain trapped in the biochar. Previous studies have shown that when the pyrolysis temperature is increased to 550 °C, most of the volatile organic compounds, such as aromatic compounds, furfural, anhydrous sugars, organic acids, and alcohol are released [40].

The calorific value is higher especially in the pyrolysis of SCL-120 at 5415 cal/g, compared to SCL-100 and SCL-130 at 5258 and 5415 cal/g, respectively. This is due to the loss of moisture and devolatilization, as well as complete decarbonization due to the pyrolysis process, which removes oxygen and forms carbon. In addition, the high carbon content also indicates that the solid residue has the potential to be utilized as biochar and purified for further use as activated carbon [8].

The calorific value increases as the pyrolysis temperature increases. This is consistent with the findings of Tsai et al. that the highest calorific value of 25.54 MJ/kg was achieved at 550 °C compared to 450 °C due to lower oxygen content and slightly higher H and C values. Previous studies have also reported that high bio-oil yields can be achieved in the temperature range of 450 to 550 °C. When the

temperature exceeds 550 °C, secondary reactions of volatile substances occur, leading to a decrease in bio-oil production. However, it is reported that the shorter the pyrolysis time, the better the bio-oil quality [41].

3.3.2. Characterization of bio-oil

The pyrolysis product in condensed bio-oil consists of two phases, the liquid phase (water-soluble organic substances) and the organic phase. The liquid is collected from separator 1 and separator 2. Separator 1 is the bio-oil product before passing through the condenser, where the specific gravity is higher, contains more tar and the color of the bio-oil product produced tends to be more concentrated. While separator 2 is a bio-oil product after passing through the condenser. The result looks like liquid and contains little tar. Furthermore, the physicochemical properties of bio-oil (organic phase) produced during pyrolysis at optimal conditions (i.e., SCL-120 and DSCL-420), were analyzed using GC-MS to identify the organic components in the samples. The identified chemical compounds with different retention times, peak area percentage, chemical formula and molecular weight are listed in Tables 3 and 4.

Table 3 lists the analyzed organic compounds and classifies them into aldehydes, ketones, acids, phenols, oxygenates and others. Thermal degradation of lignocellulosic materials (cellulose, hemicellulose, and lignin) produces benzene derivatives, phenol derivatives, and phenols in pyrolysis reactions. Small amounts of 2-cyclopentene compounds were also observed due to primary decomposition of hydrated lignocellulosic materials and secondary decomposition of char residue.

The liquid fraction obtained by condensing steam in a water condenser contained many light organic compounds, and the aqueous phase fraction was identified as carboxylic acids. In addition, the tar obtained from the pyrolysis reaction contains aromatic compounds such as phenols and 2-methoxy phenols, other pyrolysis bio-oils, and oligomers formed from the thermal decomposition of lignin at high temperatures[8].

These results indicate that lignin transforms into cyclopentanone and furanmethanol compounds with increasing temperature during the thermal degradation process. Where the furanomethanol compounds have high thermal stability and transform into high molecular weight pyrolysis vapor compounds that participate in the secondary reaction [42].

Table 3. The GC-MS analysis of the bio-oil product from SCL-120.

R.Time	Area	Area%	Name
2.532	238690	4.39	Cyclopentanone (CAS) Dumasin $$ Adipin keton $$ Adipic ketone $$ Ketocyclopentane
2.881	103376	1.9	Pyrimidine, 2-methyl- (CAS) 2-Methylpyrimidine $$ 2-Methyl-1,3-diazine
2.95	328879	6.05	2-Cyclopenten-1-one (CAS) Cyclopentenone $$ 2-Cyclopentenone $$ 3-Cyclopenten-2-one
3.37	360996	6.64	2-Furanmethanol (CAS) Furfuryl alcohol $$ Furfuralcohol $$ Furyl alcohol
3.814	322428	5.93	2(3H)-Furanone, dihydro- (CAS) Butyrolactone $$ 6480 $$ .gamma.-Butyrolactone
4.08	149564	2.75	2-Cyclopenten-1-one, 2-methyl- $$ 2-Methyl-2-cyclopentenone
4.288	80284	1.48	Pyrazine, 2,6-dimethyl- (CAS) 2,6-Dimethylpyrazine $$ 3,5-Dimethylpyrazine
5	204899	3.77	2-Cyclopenten-1-one, 3-methyl- (CAS) 3-Methyl-2-cyclopentenone
5.585	1972663	36.26	Phenol $$ Carbolic acid $$ Baker's P and S Liquid and Ointment $$ Benzenol
6.247	85878	1.58	2-Cyclopenten-1-one, 2-hydroxy-3-methyl- (CAS) Corylon $$ Corylone $$ Cycloten
6.516	97809	1.8	2,3-Dimethyl-2-cyclopenten-1-one $$ 2-Cyclopenten-1-one, 2,3-dimethyl
7.014	363622	6.68	Phenol, 2-methyl- (CAS) o-Cresol $$ o-Toluol $$ 2-Cresol $$ o-Oxytoluene
7.425	729560	13.41	Phenol, 3-methyl- (CAS) m-Cresol $$ Cresol $$ m-Kresol $$ 3-Cresol $$ m-Toluol
7.607	144139	2.65	Phenol, 2-methoxy- (CAS) Guaiacol $$ o-Methoxyphenol $$ Guajol $$ Guasol
9.207	257437	4.73	Phenol, 2-ethyl- (CAS) o-Ethylphenol $$ 1-Hydroxy-2-ethylbenzene $$ ORTHO-ETHYLPHE

In this study, the feasibility of resulting bio-oil with high concentrations of phenol and other monoaromatic compounds indicates a great potential for green chemical precursor to be applied in food preservation technology [43]. Based on data reported by Toscano et al. 2021, to obtain high-quality bio-oil products, the recommended operating temperature of the pyrolysis reactor was 450-550 °C and the heating rate was 40 K/s. However, bio-oil and biochar products produced on an industrial scale depend on mass and heat transfer, which can be affected when the sample comes into contact with the hot zone, especially for larger feedstocks. Contact of raw materials with fewer heat sources leads to temperature gradients and incomplete reactions [10].

Table 4. The GC-MS analysis of the bio-oil product from DSCL-420.

R.Time	Area	Area%	Name
2.535	346304	4.33	Pentanoic acid (CAS) Valeric acid $$ n-Valeric acid $$ Valerianic acid
2.947	413652	5.17	2-Cyclopenten-1-one (CAS) Cyclopentenone $$ 2-Cyclopentenone $$ 3-Cyclopenten-2-one
3.368	1122586	14.03	2-Furanmethanol (CAS) Furfuryl alcohol $$ Furfuralcohol $$ Furyl alcohol
3.512	80860	1.01	-
3.806	616791	7.71	2(3H)-Furanone, dihydro- (CAS) Butyrolactone $$ 6480 $$ .gamma.-Butyrolactone
4.08	154631	1.93	2-Cyclopenten-1-one, 2-methyl- $$ 2-Methyl-2-cyclopentenone
4.277	108283	1.35	isobutanoic acid 2-bromoethyl ester $$ Propanoic acid, 2-methyl-, 2-bromoethyl ester
4.999	271123	3.39	2-Cyclopenten-1-one, 3-methyl- (CAS) 3-Methyl-2-cyclopentenone
5.584	2704069	33.8	Phenol $$ Carbolic acid $$ Baker's P and S Liquid and Ointment $$ Benzenol
5.917	332507	4.16	2-Furanmethanol, tetrahydro- (CAS) Tetrahydrofurfuryl alcohol
6.243	245810	3.07	2-Cyclopenten-1-one, 2-hydroxy-3-methyl- (CAS) Corylon $$ Corylone $$ Cycloten
6.515	82273	1.03	2,3-Dimethyl-2-cyclopenten-1-one $$ 2-Cyclopenten-1-one, 2,3-dimethyl
7.012	300786	3.76	Phenol, 2-methyl- (CAS) o-Cresol $$ o-Toluol $$ 2-Cresol $$ o-Oxytoluene
7.421	574060	7.18	Phenol, 3-methyl- (CAS) m-Cresol $$ Cresol $$ m-Kresol $$ 3-Cresol $$ m-Toluol
7.606	222712	2.78	Phenol, 2-methoxy- (CAS) Guaiacol $$ o-Methoxyphenol $$ Guajol $$ Guasol
9.206	204546	2.56	Phenol, 2-ethyl- (CAS) o-Ethylphenol $$ 1-Hydroxy-2-ethylbenzene
9.779	135290	1.69	1,2-Benzenediol (CAS) Pyrocatechol $$ BRENZCATECHIN $$ C.I. 76500 $$ Fourrine 68
12.695	82844	1.04	Phenol, 3,4-dimethoxy- (CAS) 3,4-Dimethoxyphenol $$ 3,4-DIMETHOXY-PHENOL

4. Conclusions

The thermochemical conversion of sugarcane leaves was studied in a pilot scale reactor. Data analysis results suggested that compacting sugarcane leaves led to an increase in pyrolysis time up to 30 minutes. Experiments with densified feedstock consumed twice as much LPG consumption

compared to non-densified feedstock. By increasing the pyrolysis temperature from 320 °C to 420 °C, the LPG consumption was increased from 2.3 kg LPG/kg raw material to 3.13 kg LPG/kg raw material. Densification of sugarcane leaves resulted in an increase in biochar yield from 34% to 41%, while the yield of bio-oil and unconsumable gas decreased with increasing pyrolysis temperature. The physical and thermal properties of biochar indicate that the caloric value and fixed carbon content increase with increasing temperature. Various aliphatic, aromatic, ketone, benzene, and other acid compounds were found in bio-oil products suggesting a potential use as food preservation precursor material.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

The authors declare no conflicts of interest.

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