Energy Conversion and Management 278 (2023) 116723

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Characterization of pyrolysis oil produced from organic and plastic wastes using an auger reactor

M.M. Hasan [a,b,*], M.G. Rasul [a,b], M.I. Jahirul [a,b], M.M.K. Khan [c]

[a] School of Engineering and Technology, Central Queensland University, Queensland 4701, Australia
[b] Fuel and Energy Research Group, Central Queensland University, Queensland 4701, Australia
[c] School of Engineering, Computer and Mathematical Sciences, Auckland University of Technology, Auckland 1010, New Zealand

ARTICLE INFO

Keywords:
Solid waste
HDPE
Waste to energy
Fast pyrolysis
Auger reactor
Pyrolysis oil

ABSTRACT

The objective of this study is to assess the suitability of pyrolysis oils produced from organic and plastic wastes for engine application. The assessment was performed by comparing the properties of the obtained pyrolysis oils with those of standard engine fuel. A fast pyrolysis process with an auger reactor was used to convert organic wastes such as beauty leaf fruit husk (BLFH), macadamia nutshell (MNS), and municipal green waste (MGW), and plastic waste such as waste high-density polythene (HDPE) into oil. Prior to pyrolysis experiments, all the wastes were characterized using a thermogravimetric and a CHNS analyser to perform proximate and ultimate analyses. The experiments were performed using varied temperatures ranging from 400 °C to 550 °C at intervals of 25 °C, a 3-minute residence time and 2-mm feedstock particle size. The maximum yield of pyrolysis oil was obtained at 475 °C for BLFH (42.75 %), at 500 °C for MNS (45.09 %) and MGW (44.72 %) and at 525 °C for HDPE (61.29 %). The chemical and physical properties of the pyrolysis oils were analysed using Fourier transform infrared spectroscopy (FTIR), Gas chromatography–mass spectrometry (GC–MS), elemental and physicochemical properties analysis. The characterisation results reveal that the pyrolysis oils obtained from BLFH, MNS and MGW are enriched with phenolic, aromatic, and oxygenated compounds and oil obtained from HDPE contains mostly hydrocarbons and aromatics. The BLFH, MNS and MGW derived oils have higher viscosity and density and lower calorific value compared to that of HDPE derived oil. Due to these features, the oils obtained from organic wastes are not suitable for engine application without further refinement. HDPE derived oil, on the other hand, meets most of the criteria to be an engine fuel. However, a firm conclusion cannot be drawn until this oil has been tested in an engine.

1. Introduction

The generation of solid waste globally is recognised as a significant problem due to the major harm this waste does to the environment. Solid waste is created through variety of human activities. The current waste management systems, in place in most part of the world, pose significant dangers to both the natural environment and human health [1]. The ever-increasing consumption of energy which is primarily produced from fossil fuel sources has led to severe environmental deterioration. The reserves for fossil-based fuels have been depleting, and it is expected that these reserves will not last more than 50 years [2]. As a result, researchers have been looking for alternate sources to produce energy which will be renewable and be able to make good use of waste [3,4]. This will ultimately resolve both the problems of the depletion of fossil fuels and the deterioration of the environment. In this regard, different solid wastes have the potential to act as renewable sources for producing energy.

Different types of wastes, including organic, inorganic, paper, plastic, metal, cloth, glass, electronic waste, and hazardous waste, are included in the category known as solid waste. Although numerous studies have been carried out on different components of solid waste, there remain some solid wastes which have not been studied or not properly explored, despite having similar potential to already-studied solid wastes. The beauty leaf fruit husk (BLFH), macadamia nutshell (MNS) and municipal green waste (MGW) are three of those less studied wastes. These three wastes are organic wastes and generated globally on a large scale as well as possess huge potential to produce energy products. Furthermore, due to their durability, portability, and low cost

* Corresponding author at: School of Engineering and Technology, Central Queensland University, Queensland 4701, Australia.
E-mail address: engr.mmhasan@gmail.com (M.M. Hasan).

https://doi.org/10.1016/j.enconman.2023.116723
Received 11 November 2022; Received in revised form 10 January 2023; Accepted 19 January 2023
Available online 28 January 2023

across a wide range of applications, plastics have become an inescapable feature of solid waste. In the environment, plastics can persist for centuries because they are not biodegradable [5]. Ineffective management of the persistent build-up in landfills and the global ecosystems is a growing global concern that threatens coming generations [6]. There are various types of plastics. Among them high density polyethylene (HDPE) type plastic is mostly used to make plastic products [7]. As a result, most of the plastic waste is generated from HDPE plastic. For this reason, waste HDPE has been chosen in this study along with BLFH, MNS and MGW.

Pyrolysis is an emerging technology which can convert solid waste into various energy products in the form of fuels and chemicals [8]. In this process, materials with a high percentage of carbon are decomposed thermally in absence of air and energy products such as oil, char and syngas are produced. By comparison to other thermochemical processes like combustion, carbonisation, and gasification, pyrolysis results in a greater yield of a liquid energy product i.e., oil [9]. Pyrolysis oil consists of various organic compounds and the storage and transportation of it is easy and risk-free. The pyrolysis oil can be employed as a fuel in appliances like boilers and furnaces. The pyrolysis process can be broken down into slow, fast, and flash subcategories depending on the heating rate. The oil yield from fast pyrolysis is the highest [10]. For this reason specifically, researchers have a strong interest in studying this mechanism [11]. For the fast pyrolysis process to be successfully implemented, a suitable reactor must be chosen. This factor has a significant impact on the yield and quality of the pyrolysis oil [12]. A number of reactors are utilised for the fast pyrolysis of different solid wastes. Of those reactors, the auger-type offers an easy handling and smooth operation. Hence, the reactor is widely regarded as the most practical option for carrying out the fast pyrolysis process [13,14]. Therefore, an auger reactor was chosen for the present study to perform fast pyrolysis of BLFH, MNS, MGW and waste HDPE.

Many research and pilot projects have been carried out in various nations to test the viability of auger pyrolysis as a viable technology for recovering energy and raw materials from organic and plastic wastes. Table 1 provides short overview of such research endeavours. These experiments used a variety of auger reactor operating parameters using both organic and plastic wastes.

From the above literature, it is evident that organic and plastic wastes are promising sources of energy that have the potential to replace existing fossil fuels. On the other hand, the utilisation of these wastes through their conversion into various energy products will definitely reduce landfill usage and pollution in the near future [24]. Therefore, a significant number of studies are required to appropriately assess the potential of these wastes toward replacing conventional transport fuels. In this context, the pyrolysis in an auger reactor using organic and plastic wastes as feedstocks to produce energy in the form of oil can be a good approach. However, to the best of our knowledge, there have only been a handful of studies conducted with auger pyrolysis reactors using both organic and plastic wastes. Keeping it in mind, this study seeks to characterise and analyse the outcomes of using a fast pyrolysis process in an auger reactor to extract oil from BLFH, MNS, MGW, and waste HDPE. Using Fourier transform infrared spectroscopy (FTIR) and Gas chromatography–mass spectrometry (GC–MS), the qualitative and quantitative characteristics of the obtained oils were analysed in depth and also compared. The kinematic viscosity, density, pH, water content, and calorific value of pyrolysis oils were measured and analysed in order to determine whether or not these oils have the potential to be used as a fuel for transportation. Expanding the current work to extract particular desired components for synthesising of chemical products from pyrolysis oil via novel upgradation routes requires only minor process modifications to established methods.

Table 1
The research activities undertaken in auger pyrolysis reactor using various organic and plastic wastes.

Researcher	Feedstock	Operating parameters	Pyrolysis oil yield (%)
Yang et el. [15]	Waste wood pellets	T: 450 °C; RT: 1.5 min; FPS: 6 mm	54.3
Kelkar et al. [16]	Spent coffee grounds	T: 450 °C; RT: 0.5 min; FPS: 2 mm	46.7
Al-Salem et al. [17]	Waste HDPE	T: 500 °C; RT: 10 min; FPS: 4 mm	29.3
Bhattacharya et al. [18]	HDPE + Pine wood	T: 450 °C; RT: 1 min; FPS: 2 mm	38.9
Puy et al. [19]	Forestry waste	T: 500 °C; RT: 5 min; FPS: 20 mm	56.5
Lugovoy et al. [20]	Flax shive	T: 500 °C; RT: 8 *sec*; FPS: 1 mm	22.2
Nurul et al. [21]	Palm empty fruit bunch	T: 500 °C; RT: 2 min; FPS: 2 mm	58.67
Park et al. [22]	Waste LDPE	T: 500 °C; RT: 5 min; FPS: 2 mm	35.92
Sekar et al. [23]	Mixed plastics	T: 300–600 °C; RT: 3–5 hr; FPS: 10–15 mm	80

2. Materials and methods

2.1. Raw materials

The beauty leaf and macadamia fruits were collected from different parts of Australia. The MGW and waste plastics were collected from Waste Transfer Station located at Rockhampton, Australia. The collected MGW was a mixture of hedge trimmings and branches, trunks and stumps of trees. The HDPE were sorted out from waste plastic stream to use in the present study. All the materials were dried using a dryer (16CUD BenchFoods) to reduce the moisture content. A hammer was used to separate the seeds and nuts from the dry fruits. This resulted husks and shells that were then used in the pyrolysis process. After that, each of the raw materials was put through a shredder (FZ105) in order to produce particles of the desired size, which was 2 mm. Before being used in the experiments, the shredded materials were kept in an airtight container in order to prevent them from absorbing any moisture.

2.2. Pyrolysis process

An auger reactor was used in this study for the fast pyrolysis process. The reactor can be found at Central Queensland University's Fuel and Energy Research Laboratory in Rockhampton, Australia. The complete reactor setup is depicted in Fig. 1 as a picture and in Fig. 2 as a schematic diagram. Our prior work describes the auger reactor and the time–temperature profile of the fast pyrolysis process [10].

Fig. 1. The pictorial view of the whole reactor setup used in the present study.

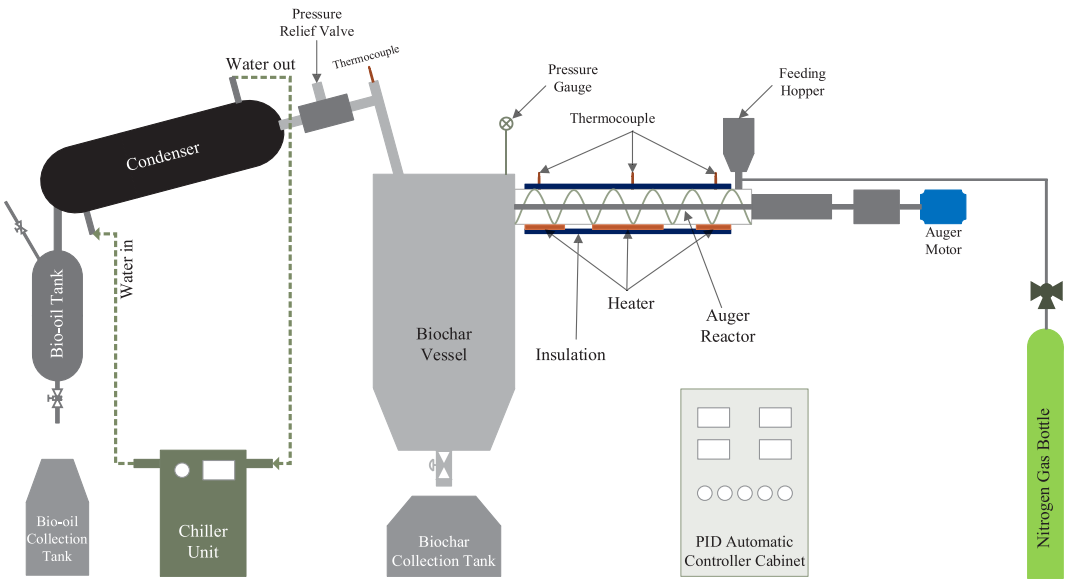

Fig. 2. Schematic diagram of auger pyrolysis reactor system used in the present study.

The auger reactor mainly consists of four parts: the feeding section, the reactor part, the char collection part, and the condensing part. The feed material is transported via a screw that is contained within the reactor and runs from one end of the reactor to the other. For each pyrolysis experiment, a batch of 2 kg of raw material was used. Before beginning the experiment, nitrogen purging was done for 15 min to remove any oxygen that might have been present in the reactor system. Because of this, the system became inert. The temperature of the pyrolysis reactor was set and the heating components in the reactor were activated accordingly to bring up to that temperature. After that, the auger motor was activated: this motor is responsible for regulating the amount of time that the feedstock spends within the reactor (residence time) by managing the speed at which the auger or screw rotates. In this study, the auger speed was set to 1 rpm, so, it took feed materials approximately 3 min to travel through the reactor. The fast pyrolysis that took place inside the reactor while the auger was transporting the feed material resulted in the production of two products - char and vapour. The vapour was passed through the condenser. The non-condensable pyrolysis product, known as syngas, was released from the system through an exhaust valve, while the condensable product, known as pyrolysis oil, was stored in a tank. After the process was finished and the system had completely cooled, the char was removed from the vessel and placed in a collection tank.

The following equation was used to determine the yield (%) of pyrolysis oil produced from the fast pyrolysis of different solid wastes [25]:

$$Y_o = \frac{m_o \times 100\%}{m_f} \quad (1)$$

where, Y_o is the yield (%) of oil, m_o is the mass (kg) of oil and m_f is the total mass (kg) of the shredded raw material used in each experiment.

2.3. Characterisation of raw materials

Dried samples of the raw materials were subjected to proximate analysis in order to ascertain their relative amounts of moisture, volatile matter, fixed carbon, and ash. In accordance with ASTM D3172-07a, a Thermogravimetric analyser (Metler Toledo TGA/SDTA 851e) was employed in the present study. The range of sample sizes used in this analysis was from 5 mg to 15 mg. At a constant rate of 5 °C per minute, the temperature was raised to 500 °C while 100 mL/min of N_2 was delivered. Each sample's percentage of weight loss was meticulously recorded. By determining the percentage of weight loss in the derivative curve, the total amount of volatile matter in each sample could be calculated. The ash percentage was calculated by burning the by-product of raw material decomposition i.e., char. Combustion occurred with the help of air. The dried samples of the raw materials were also subjected to a Vario Micro Cube CHNS analyser for ultimate analysis to calculate the elements' relative abundances, including carbon, hydrogen, nitrogen, oxygen, and sulphur. The ASTM D5373 standard was followed while performing ultimate analysis. In addition, the HHV of the various solid wastes was calculated using an oxygen-bomb calorimeter. The outcomes of characterisation studies on various solid wastes are tabulated in Table 2.

2.4. Characterisation of pyrolysis oil

The samples of pyrolysis oils were analysed using FTIR to look for existence of functional groups. In this investigation, an FTIR/ATR spectrum analyser made by Perkin Elmer was used for the analysis. A 1 cm^{-1} resolution was achieved by the analyser. Potassium Bromide (KBr) was used as the matrix material in the analyzer's Attenuated Total Reflectance (ATR) technique. Between 4000 and 400 cm^{-1} was the wave number range investigated. Detector data included measurements of infrared photon transmission through the sample chamber. The spectroscopic information was obtained using a Fourier Transform.

Gas chromatography-mass spectrometry (GC–MS) with a Varian CP3800 mass spectrometry detector was used to conduct a quantitative analysis of oils produced by the fast pyrolysis of various solid wastes. An

Table 2
Properties of different solid wastes used in the present study.

Property	BLFH	MNS	MGW	HDPE
Proximate analysis (wt%)				
Moisture	9.4	9.2	9.72	0
Volatile matter	69.24	72.3	69.57	100
Ash	3.143	0.4	0.93	0
Fixed carbon[a]	18.22	18.1	19.78	0
Ultimate analysis (wt%)				
Carbon	46.14	48.1	47.32	81.57
Hydrogen	5.81	5.24	5.14	13.26
Nitrogen	0.4	0.32	0.42	0.6
Sulphur	0.29	0.01	0.06	0.01
Oxygen[a]	37.96	36.73	37.34	4.56
HHV (MJ/kg)	18.9	19.36	18.24	45.98

oil sample was prepared for each type of solid waste before analysis. The process was started by filtering 2 mL of oil through a nylon microfilter. A 1:5 v/v methanol solvent solution was used to dilute the filtered oil. One microliter of this diluted sample was injected into the GC–MS machine. There were numerous peaks in the spectra of each individual sample. In order to determine what chemicals were already in the oil, the peaks were compared to those in the NIST database. Using this analysis, each individual compound existing in the produced pyrolysis oils could be identified.

The Flash 2000 Elemental Analyzer was used to determine the elemental composition of the pyrolysis oil. The oil samples' percentages of carbon, hydrogen, nitrogen, sulphur, and oxygen were determined using ASTM D5291. Dropping a tiny amount of oil in a tin capsule into a vertical quartz reactor full of helium and pure oxygen led to rapid combustion at extremely high temperatures. Reacting the exhaust gases yielded nitrogen, carbon monoxide, water, and sulfuric acid. These were separated on a chromatographic column and then their thermal conductivity was measured with a conductivity detector. Finally, each element's mass percentage was calculated by a software.

In order to evaluate the produced oil's potential as a fuel, its physicochemical properties were measured. ASTM D7052 and D4052 are the accepted methods for measuring kinematic viscosity and density, respectively and these methods were followed in the present study. Following the ASTM E70 standard, the pH was determined using an Omega DP24-pH metre. The measurement of water content was performed using a centrifuge sigma and the ASTM D2709 standard. Each obtained pyrolysis oil's calorific value was determined using an Oxygen-bomb calorimeter in accordance with the ASTM method D4809.

2.5. Uncertainty analysis and instrument details

The term "uncertainty in a measurement" describes the degree to which one has doubts about the accuracy of a given instrument's results. Measurement accuracy relies on the precision of the instrument and the results of an analysis of the uncertainty in the measured values. Following the guidelines of Imdadul et al. [26], an uncertainty analysis was performed by calculating the standard deviation of the means at a p-value of 0.05 (95 % confidence level). At least three independent replications of each experiment were conducted, and the mean of those results is presented here for credibility. The errors associated with the instruments used in this study are detailed in Table 3.

3. Results and discussion

3.1. Pyrolysis oil yield distribution

The distribution of the oil yield resulted from the fast pyrolysis of different solid wastes at different temperatures is presented in Fig. 3. This was carried out to determine the pyrolysis temperature that gave the maximum yield of oil for each solid waste. Three experiments were performed at each temperature and standard deviation is represented by error bars in Fig. 3. The pyrolysis temperature ranging from 400 to

Table 3
The accuracy and uncertainties of the instruments used in the present study.

Instrument	Accuracy	Uncertainty
Thermogravimetric analyzer	±0.3 %	±0.4
CHNS analyzer	±0.3 %	±0.4
Spectrum analyzer	±0.1 cm^{-1}	±0.006
Elemental analyzer	±0.3 %	±0.4
GC–MS	±0.5 %	±0.17
Viscometer	±3%	±1.28
Density meter	±0.01 g/cc	±0.28
pH meter	±0.02 pH	±1.18
Centrifuge sigma	±0.01 %	±0.28
Calorimeter	±0.05 %	±1.23

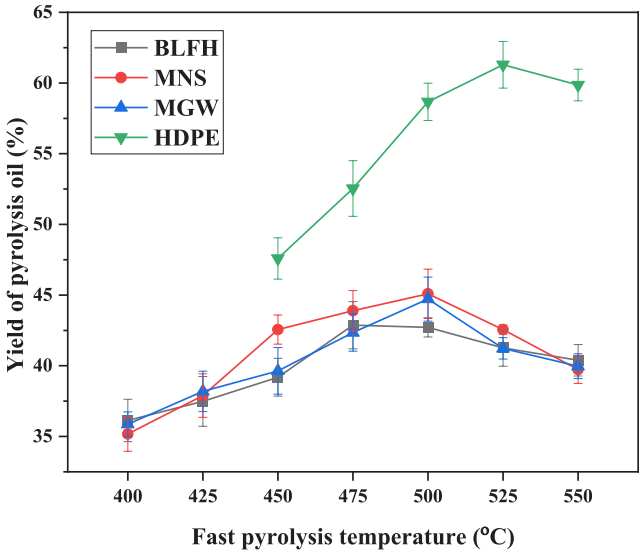

Fig. 3. The yield of pyrolysis oil obtained from the fast pyrolysis of different solid wastes at different temperatures.

550 °C was utilised in this study. It is seen from Fig. 3 that there is no data presented for HDPE derived oil at 400 °C and 425 °C. This is because of the incomplete pyrolysis occurred at these lower temperatures. During the pyrolysis process at these temperatures, the waste HDPE was converted to wax which caused the auger to stop from rotating. Consequently, the pyrolysis process was not carried further. The yield of pyrolysis oil from HDPE was 47.59 % when the temperature was increased to 450 °C. A particular temperature is required for a particular material for the pyrolysis reaction to take place and for the bonds to be easily broken [27]. In this regard, 450 °C is that temperature for waste HDPE used in this study. Then, the yield of oil was increased with increasing pyrolysis temperature up to 525 °C where the maximum oil yield of 61.29 % was obtained. The further increase of temperature to 550 °C slightly decreased the oil yield to 59.86 %. Linear and branched hydrocarbons have reduced thermal stability at higher temperatures and cracking of the C=C bond in HDPE is therefore more likely to occur at higher temperatures, leading to an increase in the yield of volatile chemicals that are favourable to the production of pyrolysis oil [24,28]. This is the reason why a higher temperature results in a greater production of oil from pyrolysis. On the other hand, the secondary cracking of primary volatiles that occurred when the temperature was 550 °C can be credited with promoting the creation of gases, which led to a minor drop in the amount of pyrolysis oil [29]. In contrast to HDPE, other three solid wastes produced oil at 400 °C and 425 °C. However, the yields of oils obtained from these three wastes at each temperature were far below from the oil yields obtained from HDPE. A material with higher volatile matter and lower ash and sulphur content is regarded as the best material for pyrolysis process and the yield of pyrolysis oil from a specific material depends on the material's volatile matter content [30]. The volatile substance decomposes and evaporates at high temperatures, releasing a number of compounds, including short-chain carbon. Most of these compounds contain gaseous components that can be condensed to produce valuable liquid energy products [31]. From Table 1, it is seen that the volatile matters of HDPE, BLFH, MNS and MGW are 100, 69.24, 72.3 and 69.57, respectively. Due to this fact waste HDPE provided highest yield of oil [32]. Similar yield of oil was found at each temperature from BLFH, MNS and MGW. This phenomenon can be attributed to similar results obtained from proximate and ultimate analyses (Table 1) of these three wastes [33]. It can be seen from Fig. 3 that similar trend like HDPE pyrolysis oil yield was followed by the yields of oils from BLFH, MNS and MGW. The yield of oil was increased with the increase of temperature up to certain point and then slightly decreased

with further increasing temperature. The maximum yield of pyrolysis oil was obtained at 475 °C for BLFH (42.75 %) and at 500 °C for MNS (45.09 %) and MGW (44.72 %). Further increasing the temperature up to 550 °C decreased the oil yield to 40.39 %, 39.74 % and 39.97 % for BLFH, MNS and MGW, respectively. This is due to the secondary cracking of pyrolysis vapour at high temperatures [34,35]. The following subsections discuss the chemical and physical characterisation results obtained from different solid wastes derived oil samples. The maximum yield of oil obtained for each waste at a certain temperature was utilised for the characterisation purpose.

3.2. FTIR analysis of pyrolysis oil

FTIR spectra provide insight into the functional groups of chemical compounds found in oils recovered from a wide range of solid wastes. Fig. 4 displays the spectra of oils produced by the fast pyrolysis of BLFH, MNS, MGW, and HDPE. It should be noted that a qualitative analysis of the spectra was performed in order to make a comparison. As can be seen in Fig. 4 that different spectral absorption bands are shaped, located, and have varying intensities. In Table 4, the functional groups present in each spectrum, along with their associated wavenumber and vibrational characteristics are depicted.

From Table 4, it is seen that there are a total of 9 functional groups identified in the obtained FTIR spectra. The functional groups of ester and carboxylic acid were identified only in the spectrum obtained for MGW derived oil and the functional groups of ketone, aldehyde, ester, and carboxylic acid were not present in the spectrum obtained for HDPE derived oil. Various types of vibrations can be seen in the spectra presented in Fig. 4 like O-H, C-H, C=O and C=C stretching vibrations and C-H bending vibration. The O-H stretching vibrations are represented by broad absorbance signals located approximately between 3000 cm^{-1} and 3600 cm^{-1} and indicating the existence of alcohols and phenols in the obtained oils [36]. The presence of alcohols and phenols in pyrolysis oil contributes to the preservation stability and keeps it from oxidising when it is exposed to the atmosphere around it [37]. The C-H stretching vibrations between 2800 cm^{-1} and 3000 cm^{-1}, as well as C-H bending vibrations between 1350 cm^{-1} and 1550 cm^{-1}, are indicators that alkanes are present in the obtained oils [38]. The presence of ketones, aldehydes, and esters in oil samples can be revealed by C=O stretching vibrations at approximately the region of 1600 cm^{-1} [39]. The presence of aldehyde reduces the capacity of pyrolysis oil to maintain its stability [40]. The C-O stretching vibrations represented by the large peak at the fingerprint region of spectrum obtained for MGW derived oil at approximately 1000 cm^{-1} point to the existence of carboxylic acids [41]. The presence of aromatic compounds can be identified by the existence of C-H and C-C stretching vibrations [42]. As functional groups of aromatics, alkanes, and alkenes were found in the obtained pyrolysis oils, it is clear that the obtained oils have the capacity to form liquid hydrocarbons [43]. The FTIR analysis can be used to rapidly categorise the wide range of chemical compounds found in pyrolysis oil, while GC–MS can be used to undertake quantitative study of the same components [44].

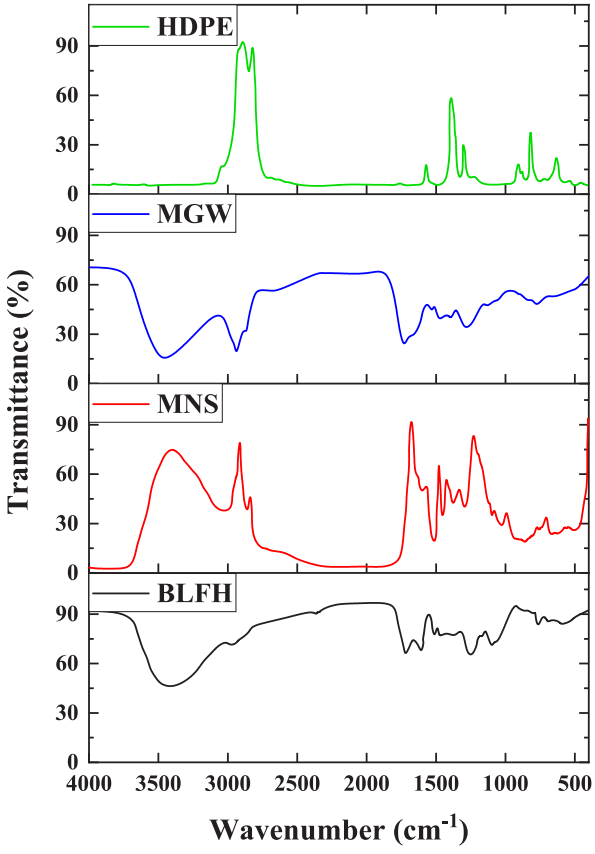

Fig. 4. The FTIR spectra of oils obtained from the fast pyrolysis of different solid wastes.

3.3. GC–MS analysis of pyrolysis oil

The obtained oils from the fast pyrolysis of BLFH, MNS, MGW and HDPE were analysed using GC–MS to detect chemical compounds contained in the oils. A chemical compound with significant peak areas and 80 % or more similarity was compiled in this study. An average of the peak areas from each triplicate test was used to determine the peak area for each compound at a specific retention time. This method of measurement confirmed the accuracy of the data. Listed in Table 5 are the major chemical compounds found in the obtained oil samples. There are a wide range of chemical compounds present in the obtained oils and some compounds were found in more than one oil sample. Benzene is an aromatic hydrocarbon which was found in MNS and MGW derived oil and the peak are 1.75 % and 1.89 %, respectively. Benzene, 1,1′-(1,3-propanediyl)bis- and benzene, 1,1′-(3-methyl-1-propene-1,3-diyl)bis- are another aromatic hydrocarbon which were identified in HDPE derived oil at high percentages i.e., 5.88 % and 5.25 %, respectively. Aromatic hydrocarbon plays a significant role in the process of making gasoline [43]. The presence of these compounds indicates that the obtained oils have the capability of producing liquid hydrocarbons. There were other aromatic compounds like pyridine and pyrrole were found in the oil obtained from MNS pyrolysis. Both of these compounds contain nitrogen and are widely used in pharmaceutical industries as intermediates in synthesis to manufacture various medicines [45]. An alcoholic compound like 1-heptadecanol was found in oil sample obtained from BLFH (1.67 %) and MNS (1.61 %). This compound is generally used in food industries as a flavoring agent [46]. Phenol, phenol, 2-methyl, phenol, 4-ethyl-2-methoxy and 3-phenyl-5-*t*-butyl-pyridazine are some of the phenolic compounds which were identified at different proportions in the GC–MS analysis of organic wastes derived oil samples. The lignin content of organic wastes is decomposed during pyrolysis process and results in high portion and wide range of phenolic compounds [47]. Phenol, one of the phenolic compounds; is frequently used as a disinfectant and antiseptic to make various household products like cleaners, mouthwash, sore throat lozenges, etc. [48]. The chemical compounds of alkanes, such as cyclopropane, undecane, dodecane, tetradecane, pentadecane and hexadecane, are also present in the obtained oils. These compounds are recognised as primary components of gasoline fuel and are commonly utilised in the chemical industry as additives for the production of a variety of different chemicals [49]. The acidic compounds such as hexadecenoic acid methyl ester and octadecanoic acid methyl ester, identified in MGW derived pyrolysis oil are commonly observed in biodiesel. These compounds have the potential to be utilised in treating serious diseases like ulcers and schizophrenia [50]. Pyrene, a

Table 4
The list of functional group present in spectra obtained for different solid wastes derived oils.

Functional group	Range of wavenumbers (cm^{-1})				Nature of vibration
	BLFH	MNS	MGW	HDPE	
Phenol	3200–3400	3200–3600	3300–3600	3050–3200	O-H stretching
Alcohol	3200–3400	3200–3600	3300–3600	3050–3200	O-H stretching
Alkane	2800–3000	2800–3000	2800–3000	2800–3000	C-H stretching
	1350–1450	1250–1400	1450–1550	1350–1500	C-H bending
Ketone	1680–1750	1680–1750	1530–1650	–	C=O stretching
Aldehyde	1680–1750	1680–1750	1530–1650	–	C=O stretching
Ester	–	–	1530–1650	–	C=O stretching
Alkene	1500–1645	1550–1650	–		C=C stretching
				850–950	C-H bending
Aromatic	1350–1450	1100–1200	1650–1750	1575–1675	C-H stretching
	690–900	400–900	600–900		C-C stretching
Carboxylic acid	–	–	920–1050	–	C-O stretching

N.D.: Not detected.

polycyclic aromatic hydrocarbon (PAH), identified in MNS derived oil, is one of the PAHs that has been researched the most due to the distinctive optical and electrical properties it possesses. It is possible to incorporate it into electrical insulation as a component [51]. There are some compounds like o-xylene, mesitylene, indane and prunetin to name a few, were only found in the oil obtained from HDPE. According to the results of the GC–MS analysis, the obtained oils contain a wide variety of valuable chemical compounds. However, in order to extract such compounds from the pyrolysis oils, an extremely efficient method of separation and purification is required. This will finally result in the transformation of such compounds into products with an increased value.

The chemical compounds detected during GC–MS analysis were organized into 12 different functional groups. Fig. 5 illustrates the total peak area percentages of each functional group's chemical compounds present in the obtained oil samples. The results of the GC–MS analysis point to the presence of a diverse range of chemicals, including those that are phenolic, aromatic, oxygenated, and hydrocarbons. The total number of functional groups present in BLFH, MNS, MGW and HDPE derived oils are 9, 11, 9 and 8, respectively. It is seen from Fig. 5 that the functional groups of aromatics and hydrocarbons are present in very higher proportions in HDPE derived pyrolysis oil compared to the oils obtained from the other three wastes. Both monocyclic and polycyclic aromatic compounds were found in the obtained oils. The aromatic functional group is important because these compounds may have far-reaching positive effects on the economy or the environment [52]. The more hydrocarbon compound present in a pyrolysis oil, the more suitability to transform it into transport fuel [53]. The less amount of hydrocarbon compounds presents in organic wastes derived oils can be attributed to the fact that reactive free radical is released during the decomposition of cellulose part of these wastes and containing of high proportion of oxygen rich compounds. This leads to the secondary cracking of pyrolysis vapour resulting the formation of light hydrocarbons [54]. The phenolic compounds have the highest total area percentages in the oils obtained from organic wastes. The presence of phenols at high concentration in the oil samples may be traced back to the primary cause, which is the breakdown of lignin structures of the organic waste [47]. The phenols in pyrolysis oil help it to resist oxidation and prolong its shelf life when exposed to air [37].

From Fig. 5, it is also seen that the obtained oils mainly from organic wastes contained oxygenated compounds at detectable concentrations. A variety of problems can arise when a fuel contains excessive amounts of oxygenated compounds, such as low stability of storage, lower energy density and calorific value as well as higher acidity [55]. Acidic chemicals in pyrolysis oil speed up polymerisation reactions in the condensation phase. This behaviour can be traced back to the presence of volatile chemical compounds in pyrolysis oil obtained from BLFH, MNS and MGW. This causes major concerns with the ageing process of oil, which restricts its use as a fuel for engines [56]. Because of the presence of acidic compounds at higher percentages in organic waste derived oil, it is hard to store these oils for extended periods [57]. Therefore, these unwanted compounds need to be extracted from these oils for improving their suitability.

3.4. Elemental analysis of pyrolysis oil

Table 6 displays the elemental concentrations that are present in the oils produced from the rapid pyrolysis of BLFH, MNS, MGW, and HDPE. These elements include carbon, hydrogen, oxygen, nitrogen, and sulphur. It is seen from the Table 6 that the percentages of carbon (84.97 %) and hydrogen (14.49 %) present in the HDPE derived pyrolysis oil is far greater than the carbon and hydrogen present in the oils obtained from BLFH (C: 57.31 %; H: 6.89 %), MNS (C: 59.27 %; H: 7.31 %) and MGW (C: 58.14 %; H: 7.01 %). This finding of carbon and hydrogen contents in pyrolysis oil from solid wastes is in good agreement with the literature [18,54,58]. The reason for higher carbon and hydrogen contents in HDPE derived oil compared to organic waste derived oil is the higher content of hydrocarbon compound (Table 4 and Fig. 5) present in the HDPE derived pyrolysis oil. High hydrocarbon content results high carbon and hydrogen contents in pyrolysis oil [29]. The general ranges of carbon and hydrogen present in organic waste derived pyrolysis oil are 55 – 60 % and 5 – 8 %, respectively [59,60]. The results obtained in the present study satisfies this criterion.

In contrast to carbon and hydrogen contents, the concentration of oxygen present in oils obtained from organic wastes is very high. The oxygen contents in BLFH, MNS and MGW derived oils are 35.2 %, 33.21 % and 34.29 %, respectively. Although these values are within the general range of oxygen content (32 – 38 %), high concentration of oxygen in pyrolysis oil leads to lower calorific value and stronger corrosive properties [54]. The percentage of oxygen present in HDPE derived oil is very low i.e., 0.27 %. This indicates its high potential to use as transport fuel. Other two elements such as nitrogen and sulphur were either found in a small proportion or not found at all in the obtained oils. For example, there was no sulphur found in MNS and HDPE derived pyrolysis oils. The presence of nitrogen and sulphur in pyrolysis oil is seen negatively since they release NO_X and SO_X when they are burned [61]. The amounts of nitrogen and sulphur in the feedstock greatly affect the corresponding amounts in the resulting pyrolysis oil. Better elemental values were found in the obtained oils compared to the feedstocks, indicating that chemical processes such as thermal decomposition of the chemical structure of the feedstock's volatile matter, cracking of pyrolysis vapour, etc. occurred during the fast pyrolysis of various solid wastes [62,63].

Table 5
List of chemical compounds present in oils obtained from the fast pyrolysis of different solid wastes.

Chemical Compound	Molecular formula	Peak area (%)			
		BLFH	MNS	MGW	HDPE
cyclopropane	C_3H_6	N.D.	0.54	0.51	N.D.
benzene	C_6H_6	N.D.	1.75	1.89	N.D.
propan-1-ol	C_3H_8O	N.D.	0.99	0.99	N.D.
ethyl acetate	$C_4H_8O_2$	N.D.	0.54	0.59	N.D.
pyrrole	C_4H_5N	N.D.	0.39	N.D.	N.D.
3-hexanone	$C_6H_{12}O$	0.81	N.D.	0.66	N.D.
toluene	C_7H_8	1.45	1.57	1.07	N.D.
3-methylbut-3-en-2-one	C_5H_8O	0.79	N.D.	N.D.	N.D.
acetic acid	$C_2H_4O_2$	N.D.	1.08	N.D.	N.D.
1-Allyl cyclopropane carboxylic acid	$C_7H_{10}O_2$	0.29	N.D.	0.49	N.D.
2-methylpropan-1-ol	$C_4H_{10}O$	0.81	N.D.	N.D.	N.D.
cyclopentanone,2-methyl	$C_6H_{10}O$	1.58	1.3	N.D.	N.D.
3-hydroxypropanal	$C_3H_6O_2$	N.D.	0.59	0.63	N.D.
ethanone,1-(2-furanyl)	$C_6H_6O_2$	1.21	N.D.	N.D.	N.D.
2-cyclopenten-1-one,3-methyl	C_6H_8O	N.D.	N.D.	1.11	N.D.
phenol	C_6H_6O	1.71	1.54	1.47	N.D.
ethylbenzene	C_8H_{10}	1.52	N.D.	0.41	1.62
o-xylene	C_8H_{10}	N.D.	N.D.	N.D.	1.62
styrene	C_8H_8	N.D.	0.91	N.D.	3.42
furan-2-carbaldehyde	$C_5H_4O_2$	N.D.	0.49	N.D.	N.D.
2-Cyclopenten-1-one,2-methyl	C_6H_8O	0.96	N.D.	N.D.	N.D.
2-Cyclopenten-1-one, 3-methyl-	C_6H_8O	1.18	N.D.	N.D.	N.D.
benzene, (1-methylethyl)-	C_9H_{12}	N.D.	N.D.	N.D.	3.09
benzene, 1-ethyl-3-methyl-	C_9H_{12}	2.18	N.D.	N.D.	1.8
cyclopentanol, 1-(1-methylene-2-propenyl)-	$C_9H_{14}O$	N.D.	N.D.	N.D.	1.65
undecane	$C_{11}H_{24}$	1.39	0.74	0.75	N.D.
cycloheptene, 1-methyl	C_8H_{14}	0.59	N.D.	N.D.	N.D.
benzene, 1-ethyl-2-methyl	C_9H_{12}	1.98	N.D.	N.D.	N.D.
cyclooctane, 1,4-dimethyl-, cis-	$C_{10}H_{20}$	N.D.	N.D.	N.D.	1.86
dodec-1-ene	$C_{12}H_{24}$	1.41	N.D.	N.D.	N.D.
dodecane	$C_{12}H_{26}$	N.D.	0.81	0.79	N.D.
piperidine-2,5-dione	$C_5H_7NO_2$	1.51	N.D.	N.D.	N.D.
2-oxopropyl acetate	$C_5H_8O_3$	N.D.	0.59	0.61	N.D.
furan-2-ylmethanol	$C_5H_6O_2$	N.D.	0.44	N.D.	N.D.
succinaldehyde	$C_4H_6O_2$	N.D.	N.D.	0.71	N.D.
butan-2-one	C_4H_8O	N.D.	0.81	N.D.	N.D.
phenol, 2-methyl	C_7H_8O	1.57	N.D.	1.72	N.D.
phenol, 2,3-dimethyl	$C_8H_{10}O$	1.28	N.D.	1.76	N.D.
benzofuran	C_8H_6O	N.D.	N.D.	0.23	N.D.
2-methoxy-5-methyl phenol	$C_8H_{10}O_2$	1.57	N.D.	1.71	N.D.
cyclooctane, 1,4-dimethyl-, cis-	$C_{10}H_{20}$	N.D.	N.D.	N.D.	1.86
hydroxylamine, O-decyl-	$C_{10}H_{23}NO$	N.D.	N.D.	N.D.	2.55
mesitylene	C_9H_{12}	N.D.	N.D.	N.D.	2.25
indane	C_9H_{10}	N.D.	N.D.	N.D.	1.65
benzene, 1-ethynyl-4-methyl-	C_9H_8	N.D.	N.D.	N.D.	1.77
cyclooctane, 1,4-dimethyl-, trans-	$C_{10}H_{20}$	N.D.	N.D.	N.D.	3.96
dodecane, 2,6,10-trimethyl	$C_{15}H_{32}$	0.33	N.D.	N.D.	N.D.
tetradecane	$C_{14}H_{30}$	0.87	0.59	0.67	N.D.
1H-indene	C_9H_8	0.98	N.D.	N.D.	N.D.
benzonitrile	C_7H_5N	0.61	N.D.	N.D.	N.D.
1-H indene, 3-methyl	$C_{10}H_{10}$	0.79	N.D.	N.D.	N.D.
prunetin	$C_{16}H_{12}O_5$	N.D.	N.D.	N.D.	1.65
tricyclo[6.4.0.0(3,7)] dodeca-1,9,11-triene	$C_{12}H_{14}$	N.D.	N.D.	N.D.	1.8
cyclododecane	$C_{12}H_{24}$	N.D.	N.D.	N.D.	4.38
naphthalene	$C_{10}H_8$	N.D.	0.91	1.05	3.24
7-tetradecene, (Z)-	$C_{14}H_{28}$	N.D.	N.D.	N.D.	4.38
1-decanol, 2-hexyl-	$C_{16}H_{34}O$	N.D.	N.D.	N.D.	4.71
pentadecane	$C_{15}H_{32}$	0.75	0.39	0.42	N.D.
pentadec-1-ene	$C_{15}H_{30}$	0.91	0.82	N.D.	N.D.
1-Tetradecanol	$C_{14}H_{30}O$	1.31	N.D.	1.23	N.D.
hexadecane	$C_{16}H_{34}$	0.27	N.D.	0.31	N.D.
hexadec-1-ene	$C_{16}H_{32}$	0.84	0.69	N.D.	N.D.
2-methoxyphenol	$C_7H_8O_2$	N.D.	1.33	N.D.	N.D.
m-cresol	C_7H_8O	N.D.	0.99	N.D.	N.D.
cyclopropylmethanol	C_4H_8O	N.D.	0.68	N.D.	N.D.
3,4-dimethylphenol	$C_8H_{10}O$	N.D.	0.99	N.D.	N.D.
phenol, 4-ethyl-2-methoxy	$C_9H_{12}O_2$	1.38	0.99	N.D.	N.D.
2-methylnaphthalene	$C_{11}H_{10}$	N.D.	0.69	0.71	N.D.
1-methylnaphthalene	$C_{11}H_{10}$	N.D.	0.53	0.45	N.D.
biphenyl	$C_{12}H_{10}$	N.D.	0.45	0.67	N.D.
cyclohexanecarboxylic acid, 2-tridecyl ester	$C_{20}H_{38}O_2$	N.D.	N.D.	N.D.	2.22
11-methyldodecanol	$C_{13}H_{28}O$	N.D.	N.D.	N.D.	1.92
1H-indene, 1-ethylidene-	$C_{11}H_{10}$	N.D.	N.D.	N.D.	1.86
1-hexadecanol	$C_{16}H_{34}O$	N.D.	N.D.	N.D.	4.86
4-nonene, 5-butyl-	$C_{13}H_{26}$	N.D.	N.D.	N.D.	4.47
2-methoxy-4-vinylphenol	$C_9H_{10}O_2$	N.D.	0.83	N.D.	N.D.
1H-indole	C_8H_7N	N.D.	0.87	N.D.	N.D.
9H-fluorene	$C_{13}H_{10}$	N.D.	0.82	N.D.	N.D.
phenol,2-methoxy-4-propyl	$C_{10}H_{14}O_2$	1.73	N.D.	1.32	N.D.
acenaphthene	$C_{12}H_{10}$	N.D.	N.D.	0.51	N.D.
3-phenyl-5-*t*-butylpyridazine	$C_{14}H_{16}N_2$	1.87	N.D.	1.42	N.D.
fluorene	$C_{13}H_{10}$	N.D.	N.D.	0.97	N.D.
phenanthrene	$C_{14}H_{10}$	N.D.	0.49	N.D.	N.D.
anthracene	$C_{14}H_{10}$	N.D.	0.94	N.D.	N.D.
2-cyclohexen-1-one	C_6H_8O	0.89	N.D.	N.D.	N.D.
naphthalene,2-methyl	$C_{11}H_{10}$	0.78	N.D.	N.D.	N.D.
1,7-dimethyl-4-(1-methylethyl)cyclodecane	$C_{15}H_{30}$	N.D.	N.D.	N.D.	2.94
benzene, 1,1′-(1,3-propanediyl)bis-	$C_{15}H_{16}$	N.D.	N.D.	N.D.	5.88
benzene, 1,1′-(3-methyl-1-propene-1,3-diyl)bis-	$C_{16}H_{16}$	N.D.	N.D.	N.D.	5.25
tert-hexadecanethiol	$C_{16}H_{34}S$	N.D.	N.D.	N.D.	2.31
benzene, 1,1′-(1,2-dimethyl-1,2-ethenediyl) bis-, (Z)-	$C_{16}H_{16}$	N.D.	N.D.	N.D.	2.64
2-hexadecanol	$C_{16}H_{34}O$	N.D.	N.D.	N.D.	2.55
4,6-dimethyldodecane	$C_{14}H_{30}$	N.D.	N.D.	N.D.	0.33
1-heptadecanol	$C_{17}H_{36}O$	1.67	N.D.	1.61	N.D.
heptadecane	$C_{17}H_{36}$	0.65	N.D.	N.D.	N.D.
naphthalene,2,3-dimethyl	$C_{12}H_{12}$	0.77	N.D.	N.D.	N.D.
naphthalene, 2,7 dimethyl	$C_{12}H_{12}$	0.78	N.D.	N.D.	N.D.
14-pentadecynoic acid, methyl ester	$C_{17}H_{34}O_2$	N.D.	N.D.	0.77	N.D.
pyrene	$C_{16}H_{10}$	N.D.	N.D.	0.43	N.D.
hexadecenoic acid, methyl ester	$C_{17}H_{34}O_2$	N.D.	N.D.	0.47	N.D.
nonadecane	$C_{19}H_{40}$	0.81	N.D.	N.D.	N.D.
1-nonadecene	$C_{19}H_{38}$	N.D.	N.D.	N.D.	1.26
octadecanoic acid, methyl ester	$C_{19}H_{38}O_2$	0.32	N.D.	0.41	N.D.
tetracosane	$C_{24}H_{50}$	N.D.	N.D.	N.D.	1.34
docosane	$C_{22}H_{46}$	N.D.	N.D.	N.D.	0.99
carbonic acid, eicosyl vinyl ester	$C_{23}H_{44}O_3$	N.D.	N.D.	N.D.	2.28
paromomycin	$C_{23}H_{45}N_5O_{14}$	0.21	N.D.	N.D.	N.D.
n-tetracosanol-1	$C_{24}H_{50}O$	N.D.	N.D.	N.D.	0.43

N.D.: Not detected.

3.5. Physicochemical properties analysis of pyrolysis oil

The physicochemical properties analysis of the obtained pyrolysis oils was carried out to assess the quality of the oils. To ascertain whether or not the obtained properties were adequate for use as engine fuels, the produced oils were compared with standard fuel properties. The physicochemical properties of the oils obtained from the fast pyrolysis of BLFH, MNS, MGW, and HDPE, as well as typical fuel properties, are listed in Table 7.

The kinematic viscosity and density are the two most important properties to determine whether a fuel is suitable for engine application or not. The kinematic viscosity is a key factor in determining

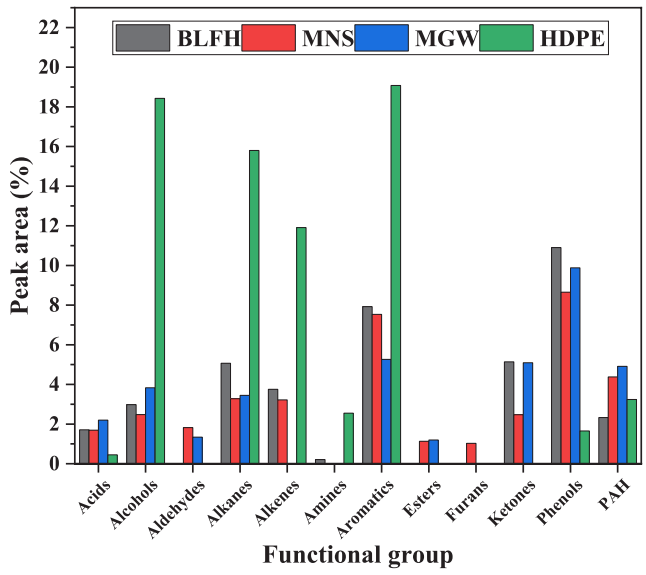

Fig. 5. Major functional groups present in the oils obtained from the fast pyrolysis of BLFH, MNS, MGW and HDPE.

Table 6
Elemental composition of oils obtained from the fast pyrolysis of different solid wastes.

Element	BLFH	MNS	MGW	HDPE
Carbon (wt%)	57.31	59.27	58.14	84.97
Hydrogen (wt%)	6.89	7.31	7.01	14.49
Nitrogen (wt%)	0.49	0.21	0.46	0.27
Sulphur (wt%)	0.11	–	0.1	–
Oxygen[a] (wt%)	35.2	33.21	34.29	0.27

[a] By difference.

atomization and spray properties, as well as the overall efficiency of the engine. The oils possessing high viscosity have a detrimental effect on the efficiency of the fuel injector because of the reduced atomization of the fuel they deliver. On the other hand, the efficiency of an engine and the characteristics of combustion are both dependent on the density of the fuel. It is seen from Table 7 that the kinematic viscosity and density of the oils obtained from BLFH, MNS and MGW are higher than that of the HDPE derived oil. The reason of high kinematic viscosity and density in organic derived oils is the existence of high lignin content which is decomposed during pyrolysis process [64]. The kinematic viscosity and density values for various solid wastes obtained in the present study are in excellent accordance with the relevant articles on similar kinds of solid wastes like empty fruit bunch [65], palm bunch [66] and waste HDPE [27]. The comparison between obtained oils and standard fuel reveals that the kinematic viscosity and density of organic wastes derived oils satisfy the criteria of ASTM Grade G and ASTM Grade D oils and HDPE derived oil satisfies the criteria of light fuel oil. Industrial burners and boilers are fuelled by ASTM Grade G and ASTM Grade D oils and internal combustion engines are fuelled by light fuel oil [67–69]. A significant refinement is required before organic wastes derived oils can be considered comparable to those of conventional fuel for engines. Another essential characteristic of an engine fuel is its pH level. For the sake of safe transportation and storage, a fuel should have a pH value that is close to neutral (pH = ~7) [70]. According to the findings of this study, the pH values of the obtained pyrolysis oils were consistently low except HDPE derived oil (pH = 5.5). This provides evidence that the obtained oils from organic wastes have an acidic character. These results are in line with the amount of acid compounds found by GC – MS analysis and consistent with the results observed by DeSisto et al. [71], Abdullahi et al. [72] and Salehi et al. [73], where a similar type of feedstock was employed to make the oil in each of those studies. The pH of HDPE derived pyrolysis oil is high because of the presence of low oxygenated compounds which makes it resistant to oxidation [74].

In regard to water present in the obtained pyrolysis oil samples, BLFH, MNS and MGW derived oils contain higher percentages of water, ranging from approximately 26 % to 30 %. Generally, the water content in organic waste derived oil lies between 15 % and 30 % [76]. Hence the water content of the obtained oils in the present study is within that range. The water in the organic waste derived oil is mainly formed from volatilisation of the feedstock's moisture and dehydration reactions that have taken place during the fast pyrolysis process. There was literally no water found in the HDPE derived pyrolysis oil which matched the criteria of an engine fuel. These results are in line with the concentration of oxygen in the obtained oils found during elemental analysis. The calorific value of a fuel has strong link with the water content of that fuel. The calorific values of the obtained oils from BLFH, MNS and MGW are 25.51 MJ/kg, 26.82 MJ/kg, and 26.13 MJ/kg, respectively. These values are far below than the calorific value of an engine fuel. However, these are comparable with published literature data using similar types of feedstocks [77–79]. These low values can be linked with the water content of the obtained oils, in that higher water content requires more energy for the existing water in the oil to be evaporated, leading to a reduced calorific value [80]. The calorific value of HDPE derived oil (42.89 MJ/kg) is comparable to the calorific value of engine fuel.

4. Conclusions and future works

In this study, the fast pyrolysis of BLFH, MNS, MGW and waste HDPE was carried out in a nitrogen environment using an auger reactor and applying similar reactor conditions like pyrolysis temperature ranging from 400 to 550 °C and residence time of 3 min. Various analytical approaches such as FTIR, GC–MS, thermogravimetric, elemental, and physicochemical properties analysis were employed to characterise the raw materials and the produced pyrolysis oils. All the raw materials contained low moisture content and high carbon content indicating its potential for pyrolysis process. The pyrolysis oil yield distribution reveals that HDPE produced maximum yield of oil (61.29 %) followed by MNS (45.09 %), MGW (44.72 %) and BLFH (42.75 %). It was found from the characterisation of produced pyrolysis oils that organic wastes derived oils contained mostly phenolic, aromatic, and oxygenated compounds and HDPE derived oil contained mostly hydrocarbons and aromatics. The pyrolysis oils obtained from BLFH, MNS and MGW had higher viscosity and density and lower calorific value compared to that of oil obtained from HDPE. The characteristic of organic wastes derived oils are similar to ASTM Grade G [67] and ASTM Grade D [68] oils. These oils are not yet in a state where they are suitable for use in an

Table 7
The physicochemical properties of BLFH, MNS MGW and HDPE derived pyrolysis oils in comparison with standard fuels.

Properties	BLFH	MNS	MGW	HDPE	ASTM Grade G [67]	ASTM Grade D [68]	Heavy fuel oil [75]	Light fuel oil [69]
Kinematic viscosity @40 °C (Cst)	12.7	11.51	12.17	1.63	Maximum 125	Maximum 125	180–420	2–4.5
Density @30 °C (g/cc)	1.16	1.06	1.13	0.78	1.1–1.3	1.1–1.3	0.99–0.995	Maximum 0.845
pH	3.9	3.8	3.6	5.5	–	–	–	–
Water content (wt%)	30.1	26.4	28.72	~0	Maximum 30	Maximum 30	~0	~0
Calorific value (MJ/kg)	25.51	26.82	26.13	42.89	Minimum 15	Minimum 15	40.6	42.6

engine. It is possible to make excellent use of them as a heating source in boilers and furnaces [81,82]. On the contrary, the characteristics of HDPE derived oil is similar to light fuel oil [69] and this oil has potential for engine application [83,84]. Oil obtained from pyrolysis of waste HDPE can be used to produce a variety of fine chemicals, while oils obtained from BLFH, MNS, and MGW can be refined into a valuable resource for the biofuel industry. New catalytic materials and separation methods could be used in the future to selectively upgrade and extract value-added components from these oils.

Based on the characterisation results obtained for BLFH, MNS and MGW derived oils, it is possible to draw the conclusion that the produced oils are not yet in a state where they are suitable for use in an engine. Upgrading oil to the appropriate level is necessary to ready it for use in engines. The HDPE derived oil satisfies most of the conditions to be a fuel suitable for engine. However, testing this oil in an engine is required to reach a solid conclusion. Therefore, the authors have planned to carry out some works in near future which include upgradation of the organic wastes derived oils by applying one of the upgradation methods available such as hydrodeoxygenation [85], catalytic cracking [86], distillation [87], esterification [88], and emulsification [89]. Additionally, the authors plan to test these oils (upgraded organic wastes derived oils and HDPE derived pyrolysis oil) in an internal combustion engine at different proportions of these oils with diesel.

CRediT authorship contribution statement

M.M. Hasan: Writing – original draft, Formal analysis, Investigation. **M.G. Rasul:** Writing – review & editing. **M.I. Jahirul:** Conceptualization. **M.M.K. Khan:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The authors would like to acknowledge the financial support provided for this study from the CRC-P project – *Australian Standard Diesel from Mixed Waste Plastics: Maximum Recovery from Waste*, project no: CRCPEIGHT000194. The authors would also like to thank CQUniversity's Fuel and Energy Research Group and Northern Oil Refinery, Queensland for providing experimental and characterisation facilities.

References

[1] Velghe I, Carleer R, Yperman J, Schreurs S. Study of the pyrolysis of municipal solid waste for the production of valuable products. J Anal Appl Pyrol 2011;92:366–75.
[2] Hosseini SE, Wahid MA. Hydrogen production from renewable and sustainable energy resources: Promising green energy carrier for clean development. Renew Sustain Energy Rev 2016;57:850–66.
[3] Jahirul MI, Brown RJ, Senadeera W, Ashwath N, Rasul MG, Rahman MM, et al. Physio-chemical assessment of beauty leaf (Calophyllum inophyllum) as second-generation biodiesel feedstock. Energy Rep 2015;1:204–15.
[4] Jahirul MI, Rasul MG, Chowdhury AA, Ashwath N. Biofuels Production through Biomass Pyrolysis —A Technological. Review 2012;5:4952–5001.
[5] Ashworth DC, Elliott P, Toledano MB. Waste incineration and adverse birth and neonatal outcomes: a systematic review. Environ Int 2014;69:120–32.
[6] Barnes DKA, Galgani F, Thompson RC, Barlaz M. Accumulation and fragmentation of plastic debris in global environments. 364 (2009) 1985-98.
[7] Chong S, Pan G-T, Khalid M, Yang TCK, Hung S-T, Huang C-M. Physical Characterization and Pre-assessment of Recycled High-Density Polyethylene as 3D Printing Material. J Polym Environ 2017;25:136–45.
[8] Tanoh TS, Ait Oumeziane A, Lemonon J, Escudero Sanz FJ, Salvador S. Green Waste/Wood Pellet Pyrolysis in a Pilot-Scale Rotary Kiln: Effect of Temperature on Product Distribution and Characteristics. Energy Fuel 2020;34:3336–45.
[9] Aysu T, Durak H. Catalytic pyrolysis of liquorice (Glycyrrhiza glabra L.) in a fixed-bed reactor: Effects of pyrolysis parameters on product yields and character. J Anal Appl Pyrol 2015;111:156–72.
[10] Hasan MM, Rasul MG, Ashwath N, Khan MMK, Jahirul MI. Fast pyrolysis of Beauty Leaf Fruit Husk (BLFH) in an auger reactor: Effect of temperature on the yield and physicochemical properties of BLFH oil. Renew Energy 2022;194:1098–109.
[11] Hasan MM, Rasul MG, Khan MMK, Ashwath N, Jahirul MI. Energy recovery from municipal solid waste using pyrolysis technology: A review on current status and developments. Renew Sustain Energy Rev 2021;145:111073.
[12] Khan S, Kay Lup AN, Qureshi KM, Abnisa F, Wan Daud WMA, Patah MFA. A review on deoxygenation of triglycerides for jet fuel range hydrocarbons. J Anal Appl Pyrol 2019;140:1–24.
[13] Brassard P, Godbout S, Raghavan V. Pyrolysis in auger reactors for biochar and bio-oil production: A review. Biosyst Eng 2017;161:80–92.
[14] Hasan MM, Rasul MG, Jahirul MI, Khan MMK. Fast pyrolysis of macadamia nutshell in an auger reactor: Process optimization using response surface methodology (RSM) and oil characterization. Fuel 2023;333:126490.
[15] Yang Y, Brammer JG, Mahmood ASN, Hornung A. Intermediate pyrolysis of biomass energy pellets for producing sustainable liquid, gaseous and solid fuels. Bioresour Technol 2014;169:794–9.
[16] Kelkar S, Saffron CM, Chai L, Bovee J, Stuecken TR, Garedew M, et al. Pyrolysis of spent coffee grounds using a screw-conveyor reactor. Fuel Process Technol 2015;137:170–8.
[17] S.M. Al-Salem, Y. Yang, J. Wang, G.A. Leeke. Pyro-Oil and Wax Recovery from Reclaimed Plastic Waste in a Continuous Auger Pyrolysis Reactor. 13 (2020) 2040.
[18] Bhattacharya P, Steele PH, Hassan EBM, Mitchell B, Ingram L, Pittman CU. Wood/plastic copyrolysis in an auger reactor: Chemical and physical analysis of the products. Fuel 2009;88:1251–60.
[19] Puy N, Murillo R, Navarro MV, López JM, Rieradevall J, Fowler G, et al. Valorisation of forestry waste by pyrolysis in an auger reactor. Waste Manag 2011;31:1339–49.
[20] Y.V. Lugovoy, K.V. Chalov, V.E. Tarabanko, A.A. Stepacheva, Y.Y. Kosivtsov. Fast Pyrolysis of Flax Shive in a Screw-Type Reactor. 44 (2021) 2056–2063.
[21] Nurul Suhada Ab R, Asadullah M, Malek NH, Amin NAS. Fast pyrolysis of oil palm empty fruit bunch in an auger reactor: bio-oil composition and characteristics. IOP Conference Series. Mater Sci Eng 2020;736.
[22] Park K-B, Jeong Y-S, Guzelciftci B, Kim J-S. Characteristics of a new type continuous two-stage pyrolysis of waste polyethylene. Energy 2019;166:343–51.
[23] Sekar M, Praveenkumar TR, Dhinakaran V, Gunasekar P, Pugazhendhi A. Combustion and emission characteristics of diesel engine fueled with nanocatalyst and pyrolysis oil produced from the solid plastic waste using screw reactor. J Clean Prod 2021;318:128551.
[24] Sekar M, Ponnusamy VK, Pugazhendhi A, Nižetić S, Praveenkumar TR. Production and utilization of pyrolysis oil from solidplastic wastes: A review on pyrolysis process and influence of reactors design. J Environ Manage 2022;302:114046.
[25] Song Q, Zhao H-Y, Xing W-L, Song L-H, Yang L, Yang D, et al. Effects of various additives on the pyrolysis characteristics of municipal solid waste. Waste Manag 2018;78:621–9.
[26] Imdadul HK, Masjuki HH, Kalam MA, Zulkifli NWM, Alabdulkarem A, Rashed MM, et al. Higher alcohol–biodiesel–diesel blends: An approach for improving the performance, emission, and combustion of a light-duty diesel engine. Energ Conver Manage 2016;111:174–85.
[27] Kumar S, Singh R. Recovery of hydrocarbon liquid from waste high density polyethylene by thermal pyrolysis. Braz J Chem Eng 2011;28:659–67.
[28] Dewangan A, Pradhan D, Singh RK. Co-pyrolysis of sugarcane bagasse and low-density polyethylene: Influence of plastic on pyrolysis product yield. Fuel 2016;185:508–16.
[29] Hassan H, Hameed BH, Lim JK. Co-pyrolysis of sugarcane bagasse and waste high-density polyethylene: Synergistic effect and product distributions. Energy 2020;191:116545.
[30] Abnisa F, Wan Daud WMA. A review on co-pyrolysis of biomass: An optional technique to obtain a high-grade pyrolysis oil. Energ Conver Manage 2014;87:71–85.
[31] Abu Bakar MS, Ahmed A, Jeffery DM, Hidayat S, Sukri RS, Mahlia TMI, et al. Pyrolysis of solid waste residues from Lemon Myrtle essential oils extraction for bio-oil production. Bioresour Technol 2020;318:123913.
[32] Aboulkas A, Makayssi T, Bilali L, El harfi K, Nadifiyine M, Benchanaa M. Co-pyrolysis of oil shale and plastics: Influence of pyrolysis parameters on the product yields. Fuel Process Technol 2012;96:209–13.
[33] Guedes RE, Luna AS, Torres AR. Operating parameters for bio-oil production in biomass pyrolysis: A review. J Anal Appl Pyrol 2018;129:134–49.
[34] Bridgwater AV. Review of fast pyrolysis of biomass and product upgrading. Biomass Bioenergy 2012;38:68–94.
[35] Hasan MM, Rasul MG, Jahirul MI, Khan MMK. Modeling and process simulation of waste macadamia nutshell pyrolysis using Aspen Plus software. Energy Rep 2022;8:429–37.
[36] Arnold S, Rodriguez-Uribe A, Misra M, Mohanty AK. Slow pyrolysis of bio-oil and studies on chemical and physical properties of the resulting new bio-carbon. J Clean Prod 2018;172:2748–58.
[37] Ren S, Ye XP. Stability of crude bio-oil and its water-extracted fractions. J Anal Appl Pyrol 2018;132:151–62.

[38] Mandal S, Bhattacharya TK, Verma AK, Haydary J. Optimization of process parameters for bio-oil synthesis from pine needles (Pinus roxburghii) using response surface methodology. Chem Pap 2018;72:603–16.
[39] Gupta GK, Mondal MK. Bio-energy generation from sagwan sawdust via pyrolysis: Product distributions, characterizations and optimization using response surface methodology. Energy 2019;170:423–37.
[40] Meng J, Moore A, Tilotta D, Kelley S, Park S. Toward Understanding of Bio-Oil Aging: Accelerated Aging of Bio-Oil Fractions. ACS Sustain Chem Eng 2014;2:2011–8.
[41] Wądrzyk M, Janus R, Vos MP, Brilman DWF. Effect of process conditions on bio-oil obtained through continuous hydrothermal liquefaction of Scenedesmus sp. microalgae. J Anal Appl Pyrol 2018;134:415–26.
[42] Singh S, Chakraborty JP, Mondal MK. Pyrolysis of torrefied biomass: Optimization of process parameters using response surface methodology, characterization, and comparison of properties of pyrolysis oil from raw biomass. J Clean Prod 2020;272:122517.
[43] Bakhtyari A, Makarem MA, Rahimpour MR. 4 - Light olefins/bio-gasoline production from biomass. In: Dalena F, Basile A, Rossi C, editors. Bioenergy Systems for the Future. Woodhead Publishing; 2017. p. 87–148.
[44] Isa KM, Daud S, Hamidin N, Ismail K, Saad SA, Kasim FH. Thermogravimetric analysis and the optimisation of bio-oil yield from fixed-bed pyrolysis of rice husk using response surface methodology (RSM). Ind Crop Prod 2011;33:481–7.
[45] Motati DR, Amaradhi R, Ganesh T. Recent developments in the synthesis of azaindoles from pyridine and pyrrole building blocks. Org Chem Front 2021;8:466–513.
[46] Albinsaad M, Scott NL, Chickos jim J. Vapor pressures and vaporization enthalpies of 1-nonadecanol. Isophytol, 2 Z- and 2 E-Phytol, and (2E,7R,11R) phytol by correlation gas chromatography. J Chem Thermodyn 2021;153:106307.
[47] Hoang Pham LK, Vi Tran TT, Kongparakul S, Reubroycharoen P, Ding M, Guan G, et al. Data-driven prediction of biomass pyrolysis pathways toward phenolic and aromatic products. Journal of Environmental. Chem Eng 2021;9:104836.
[48] C. Borelli, F. Ursin, F. Steger. The rise of Chemical Peeling in 19th-century European Dermatology: emergence of agents, formulations and treatments. 34 (2020) 1890–1899.
[49] Deneyer A, Renders T, Van Aelst J, Van den Bosch S, Gabriëls D, Sels BF. Alkane production from biomass: chemo-, bio- and integrated catalytic approaches. Curr Opin Chem Biol 2015;29:40–8.
[50] Ogunlesi M, Okiei W, Osibote EA. Analysis of the essential oil from the leaves of Sesamum radiatum, a potential medication for male infertility factor, by gas chromatography-mass spectrometry. Afr J Biotechnol 2010;9:1060–7.
[51] Mateo J, Carmo Lança M, Marat-Mendes JN. Infrared spectroscopy studies of aged polymeric insulators. Key Engineering Materials Trans Tech Publications 2002:384–7.
[52] Williams PT, Horne PA. Analysis of aromatic hydrocarbons in pyrolytic oil derived from biomass. J Anal Appl Pyrol 1995;31:15–37.
[53] Dyer AC, Nahil MA, Williams PT. Catalytic co-pyrolysis of biomass and waste plastics as a route to upgraded bio-oil. J Energy Inst 2021;97:27–36.
[54] Önal E, Uzun BB, Pütün AE. Bio-oil production via co-pyrolysis of almond shell as biomass and high density polyethylene. Energ Conver Manage 2014;78:704–10.
[55] Zhang Q, Chang J, Wang T, Xu Y. Review of biomass pyrolysis oil properties and upgrading research. Energ Conver Manage 2007;48:87–92.
[56] Thring RW, Katikaneni SPR, Bakhshi NN. The production of gasoline range hydrocarbons from Alcell® lignin using HZSM-5 catalyst. Fuel Process Technol 2000;62:17–30.
[57] Wang S, Zhao S, Uzoejinwa BB, Zheng A, Wang Q, Huang J, et al. A state-of-the-art review on dual purpose seaweeds utilization for wastewater treatment and crude bio-oil production. Energ Conver Manage 2020;222:113253.
[58] Önal E, Uzun BB, Pütün AE. An experimental study on bio-oil production from co-pyrolysis with potato skin and high-density polyethylene (HDPE). Fuel Process Technol 2012;104:365–70.
[59] Boubacar Laougé Z, Çığgın AS, Merdun H. Optimization and characterization of bio-oil from fast pyrolysis of Pearl Millet and Sida cordifolia L. by using response surface methodology. Fuel 2020;274:117842.
[60] Echresh Zadeh Z, Abdulkhani A, Saha B. A comparative production and characterisation of fast pyrolysis bio-oil from Populus and Spruce woods. Energy 2021;214:118930.
[61] Djandja OS, Yin L, Wang Z, Guo Y, Zhang X, Duan P. Progress in thermochemical conversion of duckweed and upgrading of the bio-oil: A critical review. Sci Total Environ 2021;769:144660.
[62] Isahak WNRW, Hisham MWM, Yarmo MA, Yun Hin T-Y. A review on bio-oil production from biomass by using pyrolysis method. Renew Sustain Energy Rev 2012;16:5910–23.
[63] Ahamed A, Veksha A, Yin K, Weerachanchai P, Giannis A, Lisak G. Environmental impact assessment of converting flexible packaging plastic waste to pyrolysis oil and multi-walled carbon nanotubes. J Hazard Mater 2020;390:121449.
[64] Kusrini E, Supramono D, Degirmenci V, Pranata S, Bawono AA, Ani FN. Improving the quality of pyrolysis oil from co-firing high-density polyethylene plastic waste and palm empty fruit bunches. Int J Technol 2018;9:1498–508.
[65] Rasid NSA, Asadullah M, Malek NH, Amin NAS. Fast pyrolysis of oil palm empty fruit bunch in an auger reactor: bio-oil composition and characteristics. IOP Conference Series: Materials Science and Engineering 2020;736:032021.
[66] Mohamad Azri S, Chow Mee C, Nor Kartini Abu B. Bio-oils from Pyrolysis of Oil Palm Empty Fruit Bunches. Am J Appl Sci 2009;6.
[67] Cai W, Liu R, He Y, Chai M, Cai J. Bio-oil production from fast pyrolysis of rice husk in a commercial-scale plant with a downdraft circulating fluidized bed reactor. Fuel Process Technol 2018;171:308–17.
[68] Neumann J, Binder S, Apfelbacher A, Gasson JR, Ramírez García P, Hornung A. Production and characterization of a new quality pyrolysis oil, char and syngas from digestate – Introducing the thermo-catalytic reforming process. J Anal Appl Pyrol 2015;113:137–42.
[69] Dhyani V, Bhaskar T. A comprehensive review on the pyrolysis of lignocellulosic biomass. Renew Energy 2018;129:695–716.
[70] Paramasivam B, K R, R S. Investigation and improvement on storage stability of pyrolysis oil obtained from Aegle marmelos de-oiled seed cake. Energy Sources Part A 2021;43:953–67.
[71] DeSisto WJ, Hill N, Beis SH, Mukkamala S, Joseph J, Baker C, et al. Fast Pyrolysis of Pine Sawdust in a Fluidized-Bed Reactor. Energy Fuel 2010;24:2642–51.
[72] Abdullahi N, Sulaiman F, Safana AA. Bio-oil and biochar derived from the pyrolysis of palm kernel shell for briquette. Sains Malaysiana 2017;46:2441–5.
[73] Salehi E, Abedi J, Harding T. Bio-oil from Sawdust: Effect of Operating Parameters on the Yield and Quality of Pyrolysis Products. Energy Fuel 2011;25:4145–54.
[74] Chen W, Shi S, Zhang J, Chen M, Zhou X. Co-pyrolysis of waste newspaper with high-density polyethylene: Synergistic effect and oil characterization. Energ Conver Manage 2016;112:41–8.
[75] Kontoulis P, Kazangas D, Doss TP, Kaiktsis L. Development and CFD Validation of an Integrated Model for Marine Heavy Fuel Oil Thermophysical Properties 2018;144:04018059.
[76] Kumar R, Strezov V, Weldekidan H, He J, Singh S, Kan T, et al. Lignocellulose biomass pyrolysis for bio-oil production: A review of biomass pre-treatment methods for production of drop-in fuels. Renew Sustain Energy Rev 2020;123:109763.
[77] Ahmed A, Abu Bakar MS, Sukri RS, Hussain M, Farooq A, Moogi S, et al. Sawdust pyrolysis from the furniture industry in an auger pyrolysis reactor system for biochar and bio-oil production. Energ Conver Manage 2020;226:113502.
[78] Ahmed A, Abu Bakar MS, Azad AK, Sukri RS, Phusunti N. Intermediate pyrolysis of Acacia cincinnata and Acacia holosericea species for bio-oil and biochar production. Energ Conver Manage 2018;176:393–408.
[79] Park JY, Kim J-K, Oh C-H, Park J-W, Kwon EE. Production of bio-oil from fast pyrolysis of biomass using a pilot-scale circulating fluidized bed reactor and its characterization. J Environ Manage 2019;234:138–44.
[80] Budarin VL, Clark JH, Lanigan BA, Shuttleworth P, Breeden SW, Wilson AJ, et al. The preparation of high-grade bio-oils through the controlled, low temperature microwave activation of wheat straw. Bioresour Technol 2009;100:6064–8.
[81] Islam MR, Parveen M, Haniu H. Properties of sugarcane waste-derived bio-oils obtained by fixed-bed fire-tube heating pyrolysis. Bioresour Technol 2010;101:4162–8.
[82] Ji-lu Z. Bio-oil from fast pyrolysis of rice husk: Yields and related properties and improvement of the pyrolysis system. J Anal Appl Pyrol 2007;80:30–5.
[83] Kumar S, Prakash R, Murugan S, Singh RK. Performance and emission analysis of blends of waste plastic oil obtained by catalytic pyrolysis of waste HDPE with diesel in a CI engine. Energ Conver Manage 2013;74:323–31.
[84] Saha D, Sinha A, Roy B. Critical insights into the effects of plastic pyrolysis oil on emission and performance characteristics of CI engine. Environ Sci Pollut Res 2021;28:44598–621.
[85] Shafaghat H, Kim JM, Lee I-G, Jae J, Jung S-C, Park Y-K. Catalytic hydrodeoxygenation of crude bio-oil in supercritical methanol using supported nickel catalysts. Renew Energy 2019;144:159–66.
[86] Ibarra Á, Hita I, Arandes JM, Bilbao J. Influence of the Composition of Raw Bio-Oils on Their Valorization in Fluid Catalytic Cracking Conditions. Energy Fuel 2019;33:7458–65.
[87] de Castro DAR, da Silva Ribeiro HJ, Ferreira CC, de Andrade Cordeiro M, Guerreiro LHH, Pereira AM, et al. Fractional Distillation of Bio-Oil Produced by Pyrolysis of Açaí (Euterpe oleracea) Seeds. Fractionation 2019:61.
[88] Sondakh RC, Hambali E, Indrasti NS. Improving characteristic of bio-oil by esterification method. IOP Conference Series: Earth and Environmental Science 2019;230:012071.
[89] Jiang X, Ellis N. Upgrading Bio-oil through Emulsification with Biodiesel: Mixture Production. Energy Fuel 2010;24:1358–64.