Small Industrial Scale Pyrolysis of Oil Palm Shells and Characterizations of their Products

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***Abstract** – Biomass in the form of oil palm shells (OPS) from Elaeis guineensis were pyrolysed in a small industrial scale system which was externally heated by liquefied petroleum gas while the emissions from the process were condensed. The raw OPS were characterized via proximate, elemental and thermogravimetric analysis. Pyrolysis runs were performed using a heating rate of about* 2 °C min^{-1} *and at a terminal temperature of 600 °C. The OPS char with 83.30% fixed carbon and a calorific value of 30.83 MJ kg^{-1} was produced. The empirical formula of the OPS oil with a calorific value of 32.44 MJ kg^{-1} was established as* $CH_{1.32}O_{0.24}N_{0.03}$. *Functional group compositions of the OPS oil indicated that only moderate quantities of hydrocarbons were present, while oxygenated compounds dominated. A lot of chemical constituents were identified in the OPS vinegar with acetic acid and phenol being the main constituents.*

***Keywords** – Characteristic, oil palm shell, slow pyrolysis.*

1. INTRODUCTION

Malaysia is one of the largest producers of *Elaeis guineensis* palm oil in the world thus resulting in an abundance of palm biomass. The biomass has been identified as a valuable natural resource, either as a potential source of renewable energy or of value added by-products [1]. The solid biomass from the palm oil industry consists of oil palm shells (OPS), mesocarp fibres, empty fruit bunches, fronds and trunks. For every tonne of fresh fruit bunches processed, about 55 kg of OPS, the hard portion of the oil palm seed that is broken to extract oil from the kernel, is generated. The dry matter yield of OPS is 0.938 tonnes per ha per year and the energy potentially available from the biomass is 19.50 GJ per ha per year [2]. The availability of OPS can be estimated from the planted area of over 4.30 million hectares with oil palms as of 2007 [3]. The OPS and fibres are conventionally used as fuels to generate heat for boilers in palm oil mills. Hussain *et al.* have reported the analysis of biomass-residue-based cogeneration system. The boilers produce high pressure and temperature steam which expand in a back pressure steam turbine and produces enough electric power for the internal needs of the mills [4]. However, more recently, the commercial scale carbonization of OPS to produce solid char, bio-oil and pyroligneous acid has become popular.

OPS share the same characteristics as coconut shells. They possess a highly complex pore structure and fibre matrix, iodine values and superior hardness making them the raw material of choice for the production of premium activated carbon [5], [6]. Besides, they are also good raw materials for fuel briquettes. OPS char has high energy content and due to its complex fibre matrix structure, the energy is released slowly during combustion. Since OPS are of smaller shell size, they are easier to carbonize for mass production, and the resulting char can be pressed into heat efficient biofuel briquettes [7], [8]. During the slow pyrolysis of wood, wood vinegar as a by-product can be recovered [9]. Similarly in the pyrolysis of OPS, a pyroligneous acid, referred to as OPS vinegar can also be recovered. This product has a variety of applications and is comparable to wood vinegar which is widely used in China and Japan [10], [11].

Even though OPS have been pyrolysed on a commercial scale [12], reliable data on the pyrolysis reactions and product characterizations are still lacking, hence a project was initiated at Universiti Sains Malaysia to study in greater detail the production of OPS char, OPS oil and OPS vinegar using a small industrial scale system that better mimics commercial set-ups.

2. MATERIALS AND METHODS

Raw Materials

Fig. 1. A picture of a few pieces of broken OPS.

Fresh OPS (see Figure 1) were procured from an oil palm mill in Nibong Tebal, Penang. The samples received were in broken form and of sizes of about 1-2 cm with a bulk density of about 440 kg m^{-3} and were air-dried for one week. It has been reported by Wan and Wan that OPS consist of 29.7% cellulose, 47.7% halocellulose and

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53.4% lignin [13]. Each of these components will contribute towards the formation of volatiles, gases and chars when OPS undergo the pyrolysis process. Proximate analysis, elemental composition and calorific value determinations were done on the raw OPS samples using standard ASTM procedures. The solid and apparent densities of OPS were determined using an AccuPyc 1330 Pycnometer as per ASTM D-2856.

Thermal and Kinetic Studies

The thermal characteristics of OPS were analyzed using a thermogravimetric analyzer (TGA/SDTA851) as per ASTM D-3850 to determine the loss in weight of the sample as a function of temperature and time. Particles of about 1 mm size were heated in a dynamic nitrogen gas flow of 30 cm^3 min^{-1} over a temperature range from ambient to 900 ^oC. A pre-study of the thermal characteristics and kinetics before the actual pyrolysis experiment is helpful in developing a suitable thermochemical conversion process for eventual use.

Pyrolysis Process

Slow pyrolysis of the OPS was carried out using a small industrial scale pyrolyser. The pyrolyser is basically a cylindrical stainless-steel vessel surrounded by a layer of ceramic fibre as heat insulator. The dimensions of the sample holder are 75 cm in length and 25 cm in internal diameter. The pyrolyser was heated externally using liquefied petroleum gas (LPG) and the pyrolysis temperatures were measured by a thermocouple. The pyrolysis experiments were performed with about 13 kg of rather dry OPS packed inside the pyrolyser. The emissions of the pyrolysis process were recovered using a condenser. The liquid products were collected in an ice-cooled container and followed by decantation the next day while the non-condensable gaseous product was simply emitted into the atmosphere.

Heating the bottom of the closed vessel externally was carried out using a slow fire. When the desired terminal temperature of 600 ^oC was attained, pyrolysis was allowed to proceed at that temperature for a few hours until the process is deemed to be complete. For this terminal temperature, 3 pyrolysis runs were carried out. After each run the sample holder was left inside the pyrolyser for at least 24 hours for it to cool before the char yield was determined and the yield of condensable emissions was determined after the decantation. It was found that the condensate separated into an aqueous fraction and a tarry fraction. Mass balance analyses were done on the yields of the products where the non-condensable gaseous yield was determined by difference.

Solid and Liquid Products Analyses

The OPS char produced were left exposed in the laboratory environment for a further 2 days before they were milled into granules for the analysis of quality. Proximate analyses were performed on 3 samples of each pyrolysis run for moisture, ash and volatile contents as per ASTM D-3173, D-3174 and D-3175 respectively. Besides that, elemental analyses on the OPS chars produced were done using a CHNS analyzer (Perkin Elmer 2400 Series II). The calorific values were determined using an adiabatic oxygen Bomb Calorimeter (Parr 1261). Standard procedures were adopted for all of the above analyses. The solid and apparent densities of powdered char were determined using an AccuPyc 1330 Pycnometer as per ASTM D-2856.

The liquid product collected for analysis was divided into 2 fractions: OPS oil, the tarry fraction and OPS vinegar, the aqueous fraction. Fourier transform infrared spectroscopic analysis was performed on a representative sample of the *OPS oil* using a Perkin Elmer FT-IR 2000 spectrometer. A thin uniform layer of the oil was placed on a KRS-5 window cell and exposed to the IR beam. The functional chemical groups in OPS oil were identified from their FT-IR spectra. Standard oil characteristics tests were also carried out to determine the OPS oil properties. The major chemical compounds in the OPS vinegar were identified using a Gas Chromatography Mass Spectroscopy spectrometer (Thermo Finnigan GC-MS). Some physical properties of the OPS vinegar were also determined. Standard procedures for the operation of the above spectrometers were followed.

3. RESULTS AND DISCUSSION

Raw Material Characteristics

The followings are the compositions and properties of the air-dried fresh raw OPS in Table 1 and their thermal characterizations in Figure 2 and Table 2.

The data in Table 1 indicate that raw OPS have a rather high volatile content and a low amount of fixed carbon. The ash content however appears to be of low level when compared with other oil palm wastes. As expected the higher calorific value of the raw OPS is lower than that of coal. The elemental analysis results indicate that OPS are carbon and oxygen rich feedstocks with low levels of hydrogen and trace quantities of nitrogen and sulfur.

Though the chemistry of biomass is quite complicated, it is generally assumed that biomass has three major constituents: hemicellulose, cellulose and lignin. The thermogravimetric (TG) and derivative thermogravimetric (DTG) profiles for OPS recorded for 30 to 900 ^oC with a heating rate of 10 ^oC min^{-1} are shown in Figure 2.
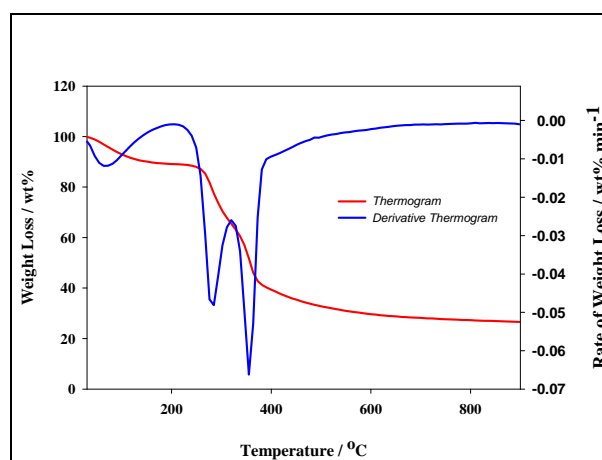

Fig. 2. TG and DTG profiles for pyrolysis of OPS.

Note: The initial weight of the OPS sample is 13.60 mg

Table 1. Characterizations of the raw OPS (the values shown in brackets are the average from 3 runs).

Proximate analysis (wt. %)		Elemental analysis (wt. %)	
Moisture	5.21 – 6.57 (5.97)	Carbon	49.25 – 49.97 (49.71)
Volatiles	70.52 – 76.35 (73.20)	Hydrogen	5.24 – 6.21 (5.79)
Ash	2.52– 3.04 (2.79)	Nitrogen	0.36 – 0.42 (0.40)
*Fixed Carbon	14.04 – 21.75 (18.04)	Sulphur	0.01 – 0.04 (0.02)
		*Oxygen	40.32 – 42.62 (41.29)
GCV (MJ kg^{-1})	20.43 – 22.07 (21.52)	H/C molar ratio	1.40
		O/C molar ratio	0.62
Solid density (g cm^{-3})	1.56	N/C molar ratio	0.01
Apparent density (g cm^{-3})	1.52	S/C molar ratio	0.0002
Total porosity (%)	2.56	Empirical formula: **$CH_{1.40}O_{0.62}N_{0.01}S_{0.0002}$**	

* Calculated by difference.

The initial 10.81% weight loss (30 - 200 $^{\circ}$C) is attributed to the evaporation of moisture from the OPS sample. The second step of 23.52% weight loss (200 - 320 $^{\circ}$C) corresponds to the thermal decomposition of hemicellulose while the third step of 38.99% weight loss (320 - 900 $^{\circ}$C) corresponds to the decomposition of cellulose and lignin. Lignin undergoes gradual decomposition over a wide temperature interval (300 - 900 $^{\circ}$C) and eventually only 26.57% of char is left behind as residue in the sample holder.

From the DTG curve, two distinct peaks at temperature around 280 $^{\circ}$C (at a devolatilisation rate of 0.049 weight loss min^{-1}) and 360 $^{\circ}$C (at a devolatilisation rate of 0.067 weight loss min^{-1}) correspond to the thermal decomposition of hemicellulose and cellulose respectively. However both curves indicate that the devolatilisation was initiated at about 240 $^{\circ}$C and approaches near completion and with an acceptable char yield at about 600 $^{\circ}$C. As such, the small industrial scale pyrolysis system was subsequently operated with slow heating from ambient to a terminal pyrolysis temperature of about 600 $^{\circ}$C. It is not necessary to raise the temperature of the kiln beyond this value but to maintain it as the devolatilisation at the final stage is minimal. This would therefore reduce energy input to the process.

Their kinetic parameters of thermal decomposition were calculated using the Arrhenius equation, using a three-step consecutive reaction model [14]:

$$\frac{d\alpha}{dt} = k(1-\alpha)^n \tag{1}$$

where α is defined as $(w_0 - w)$ / $(w_0 - w_f)$, w_0 is the initial mass of the sample, w is the actual mass at time t, w_f is the mass of residue at the end of the reaction, t is the reaction time, n is the reaction order, and k is the rate constant of reaction which is defined as:

$$k = Ae^{-E/RT} \tag{2}$$

where A is the pre-exponential factor and E is the apparent activation energy of the decomposition. Both parameter values with their n-order of reactions and also the thermal degradations at different temperature regimes are listed in Table 2.

Table 2. Kinetic parameters and total degradation during thermal decomposition.

Kinetic Parameter	Temperature zone ($^{\circ}$C)			
	Entire reaction zone	200 - 320	320 - 500	500 - 900
A (s^{-1})	6.94E+9	3.36E+13	8.29E+11	1.08E+4
E (kJ/mol)	100	132	129	63
n	2.5	1.0	2.08	1.2
R^2	0.9681	0.9938	0.9426	0.9238
Total degradation (%)	73.43	23.52	32.86	6.06

The weights of raw OPS that were packed into the sample holder of the small industrial scale system for each of the 3 pyrolysis runs were found to be about 11 to 14 kg. As the biomass was heated up, the initial stage involved the removal of moisture from the OPS at temperatures of less than 110 $^{\circ}$C. As the experiment proceeded, devolatilisation was initiated at about 240 $^{\circ}$C and was complete by about 600 $^{\circ}$C. The release of white volatiles was observed to end after 6 hours when the heating rate of about 2 $^{\circ}$C min^{-1} was applied. The condensates collected in the ice-cooled container were found to consist of a rather viscous black tarry component floating in a fairly clear brownish solution but on standing, this tarry component eventually precipitated to the base of the container.

Chars, light and heavy organic liquids, water and non condensable gases form in varying amounts when biomass is pyrolysed at varying conditions. Their yields depend not only on the raw material composition but on the heating rate and terminal pyrolysis temperature as well [15] – [20]. In this study when OPS were pyrolysed, char was the main product, with condensates as a by-product.

Yield of char is defined as:

$$\frac{\text{Weight of OPS char produced}}{\text{Weight of dry raw OPS used}}$$

and yield of condensates is defined as:

$$\frac{\text{Weight of OPS condensates collected}}{\text{(whether tarry or aqueous fraction)}}{\text{Weight of dry raw OPS used}}$$

According to the above definitions, the average percentage yields of the 4 pyrolysis products are presented in Figure 3.

Pyrolysis runs were operated with a heating rate of about 2 $^{\circ}$C min^{-1} instead of 10 $^{\circ}$C min^{-1} so as to increase the yield of OPS char as a slower rate of heating would provide a longer residence time that favours char formation. This indeed was found as the above char yield of nearly 40% is much higher than the yield of about 31% with the TGA studies. The solid product characterizations from various quality analyses of the OPS char were presented in Tables 3 and 4.
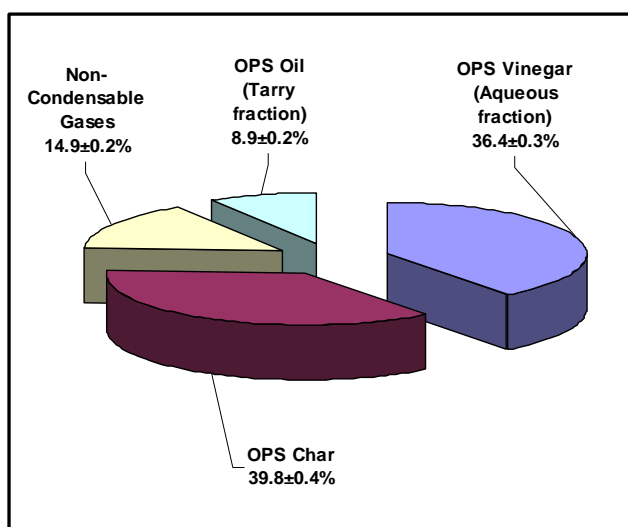

Fig. 3. Yields from pyrolysis of OPS. Each value is the average of 3 pyrolysis runs.

Table 3. The proximate analysis and elemental analysis of OPS char produced (values in the brackets represent the averages from 3 samples for each pyrolysis run).

Proximate analysis (wt. %)		Elemental analysis (wt. %)	
Moisture	3.89 – 6.04 (4.65)	Carbon	83.02 – 87.01 (85.22)
Volatiles	6.87 – 10.02 (8.35)	Hydrogen	1.52 – 2.54 (1.90)
Ash	2.98 – 5.01 (3.70)	Nitrogen	0.43 – 0.65 (0.51)
*Fixed Carbon	78.93 – 86.26 (83.30)	Sulphur	0.00 – 0.02 (0.01)
		*Oxygen	4.77 – 12.05 (8.66)

* Calculated by difference

Table 4. A comparison of energy content and density of OPS char with Pittsburgh coal (values in the brackets represent the average from 3 samples for each pyrolysis run).

Parameter	OPS Char	Pittsburgh Coal
Higher calorific value (MJ kg^{-1})	30.21- 31.45 (30.83)	30.0
Apparent density (g cm^{-3})	1.38 - 1.42 (1.40)	1.22
Solid density (g cm^{-3})	1.81 - 1.83 (1.82)	1.46
Total porosity (%)	23.08	16.44

Table 3 shows the results of the proximate analysis and elemental analysis done on the OPS char. The char exhibited a high fixed carbon or pure carbon and low ash content. The presence of traces of nitrogen and sulfur show that the char is environment friendly. Therefore the OPS char would perform the best quality among the various types of solid fuel from oil palm residues due to its high content of carbon. Besides that, the energy content, densities and porosity of OPS char which were also determined are tabulated in Table 4 and compared to the Pittsburgh coal data from reference [21].

The data in Table 4 indicate that the energy content of OPS char is increased by 1.5 fold while the total porosity [5] is increased by 9 folds after it is pyrolysed

when compared to the raw material. The average calorific value of OPS char is comparable to Pittsburgh coal thus indicating that the char produced has the potential to replace that fossil fuel. In addition, OPS char is more porous than coal. The above qualities and uniformity of the solid product indicate that the OPS char is not only suitable for the production of solid biofuel briquettes but also activated carbon.

The condensates after 24 hours of standing at room temperature were still found to be not homogeneous as the separation into 2 distinct fractions, one of viscous tar and the other of a less oily brownish aqueous phase was still observed. Some of the tar adhered to the inner wall but most precipitated to the base of the container. As indicated

earlier we labeled the black viscous tarry fraction as *OPS oil* while the brownish liquid is referred to as *OPS vinegar*. The characterizations of these liquid products were presented in Figure 4 and Tables 5 to 9.

Table 5 shows the functional group composition of the OPS oil, obtained from the FT-IR spectra in Figure 4. The data show that OPS oil consists of carboxylic acids,

phenols, alcohols, ketones, alkanes, alkenes, aromatic rings, water etc. Due to large amounts of oxygenated components present, the bio-oil thus has a polar nature and does not mix readily with hydrocarbons. Therefore, upgrading of the bio-oil should be done to remove the oxygen and improve the bio-oil composition [22], [23].
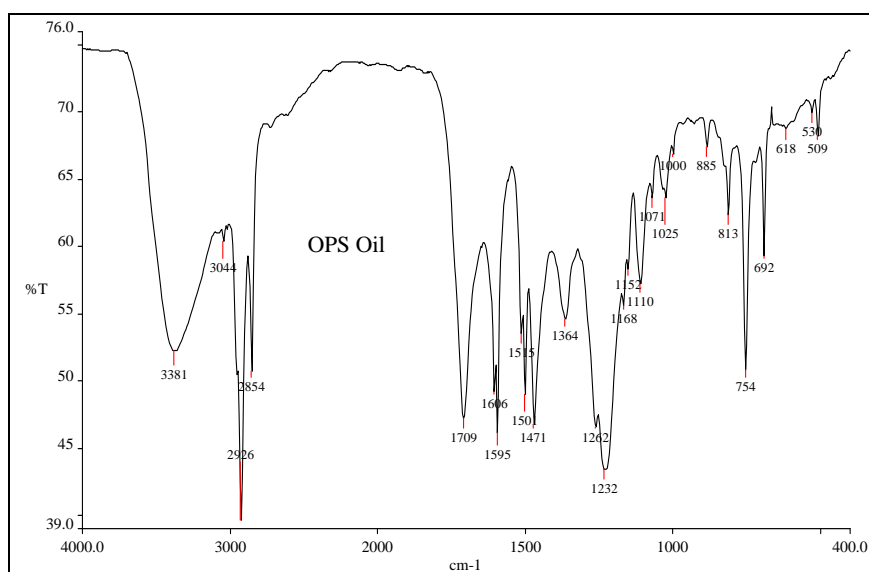

Fig. 4. FT-IR spectra of the OPS oil.

Table 5. FT-IR functional group compositions of the OPS oil.

Wave number range (cm^{-1})	Wave number (cm^{-1})	Group	Class of compound
3300-3600	3381	O-H stretching	Polymeric O-H, water impurities.
3050-2800	3044, 2926, 2854	C-H stretching	Alkanes
1750-1650	1709, 1606	C=O stretching	Ketones, aldehydes, Carboxylic acids.
1650-1580	1595	C=C stretching	Alkenes
1550-1490	1515, 1501	NO$_2$ stretching	Nitrogenous compounds
1470-1350	1471, 1364	C-H bending	Alkanes
1300-950	1262, 1232, 1168, 1152, 1110, 1071,1025, 1000	C-O stretching O-H bending	Primary, secondary and tertiary alcohols, phenols, esters, ethers.
915-650	885, 813, 754, 692		Aromatic compounds

Table 6. Comparison of the properties of OPS oil from slow and fast pyrolysis.

Bio-oil Physical Properties	Method	OPS Oil from Slow Pyrolysis	OPS Oil from Fast Pyrolysis
Colour	Visual	black	black
Odour	Smell	acrid smoky	acrid smoky
pH	pH meter	2.76	2.70
Water Content (%)	ASTM D-4928	4.04	10.0
Acidity (%)	ASTM D-1093	6.40	NA
Sulfur (%)	ASTM D-1266	0.12	0.0
Ash (%)	ASTM D-482	0.09	0.10
Specific Gravity (g cm^{-3})	ASTM D-1298	1.02	1.20
Viscosity at 40 ^{o}C (cSt)	ASTM D-445	25.13	14.63
Flash Point (^{o}C)	ASTM D-93	34	54
Pour Point (^{o}C)	ASTM D-97	3.0	-10
Higher Calorific Value (MJ kg^{-1})	ASTM D-5865	32.44	22.10

The physical properties of the OPS oil, determined by standard test procedures are tabulated in Table 6. Their characteristics were compared to the OPS oil from fast pyrolysis studies reported by [24]. The water content in fast pyrolysis oil was higher because it is a single phase liquid. Both the oil products have higher viscosity when compared to Malaysian diesel (4.0 cSt at 40 $^{\circ}$C). The lower flash point of OPS oil suggests that this oil can be easily burnt. Hence it is unsafe to store it at room temperature. Nevertheless the above fuel properties including its rather high calorific value indicate that the OPS oil can be directly used as fuel and it is also convenient for transportation and utilization. Instead of using LPG to operate an industrial-scale pyrolysis process, it is practical possibility to use the OPS oil as source of external heat to the pyrolyser.

Table 7 shows the elemental composition of the OPS oil and bio-oil from hardwood [25]. Except for oxygen, it was found that the carbon, hydrogen, nitrogen and sulfur contents of OPS oil are somewhat higher than that of hardwood bio-oil. Even so, as a whole, these two types of oil are quite similar and indicate that OPS could produce a bio-oil that is at least comparable to that from hardwood. The OPS oil contains only small concentrations of sulphur and nitrogen which will become pollutants. At any heating rate, the rather high oxygen content of these bio-oils will affect their fuel quality [26].

OPS vinegar is a quite complex acidic mixture. Its colour would easily change after standing in the laboratory and this is due to photochemical reactions [27].

There are numerous kinds of chemical compounds present with water as the main constituent as shown in Table 8. The other constituents are organic acids, phenolic compounds, alkone compounds, alcohol compounds and others as identified and are listed in Table 9.

From the GC-MS analysis, of the water free component, phenol and its derivatives were found to contribute 38.6% to this component. The high proportion of phenols found indicates that value-added chemicals can be extracted from OPS vinegar. A lot of chemical constituents in the OPS vinegar are similar to those are found in pyroligneous acid from *Rhizophora Apiculata* with some of them having antibacterial, antioxidant and antifungal properties [28].

Due to its acidic contents, Sembawa Rubber Research Station in Palembang, Indonesia has used OPS vinegar as an effective coagulant for field latex. Its antibacterial, antioxidant and antifungal properties also contribute to the high plasticity retention index (PRI) value in post-processed rubber [29]. OPS vinegar can also be used to reduce the fouling odor emitted from sewage treatment plants, poultry processing factories, tannery production, landfill sites, scrubber towers, rubber industries and food processing plants [30]. In addition, it can also be utilized for soil improvement just like bamboo vinegar which has a positive effect on plant growth at high dilution rates such as 300-1,000 times [31].

Table 7. A comparison of the results of the elemental analysis of OPS oil with bio-oil from hard-wood (each value for the OPS oil is the average of three runs).

Elemental Analysis	Method	OPS Oil (wt. % daf)	Bio-oil (wt. % daf)
Carbon	ASTM D-5373	68.34 – 68.79 (68.63)	55.5
Hydrogen	ASTM D-5373	7.02 – 8.04 (7.54)	6.7
Oxygen	By diff.	20.49 – 22.78 (21.63)	37.7
Nitrogen	ASTM D-5373	1.81 – 2.54 (2.08)	0.1
Sulphur	ASTM D-4239	0.05 – 0.14 (0.12)	0.00
H/C	Molar ratio	1.32	1.45
O/C	Molar ratio	0.24	0.51
N/C	Molar ratio	0.03	0.002
S/C	Molar ratio	0.00	0.00
Empirical formula		$CH_{1.32}O_{0.24}N_{0.03}$	$CH_{1.45}O_{0.51}N_{0.002}$

Table 8. Characteristics of the OPS vinegar.

Physical Properties	Method	OPS Vinegar
Colour	Visual	Brown
Odour	Smell	Smoky odor
Specific Gravity	ASTM D-1298	1.021
Water Content	ASTM D-4928	82.4%
Acidity	ASTM D-1093	6.94%
pH	pH meter	2.88

Table 9. Constituents of OPS vinegar.

Chemical compound identification	Relative quantity (%)
Methanol	10.7
1-Hydroxy-2-propanone	0.9
3-Methyl-1H-pyzol	0.2
2-Methyl-2-cyclopenten-1-one	0.6
Acetic acid	35.7
Furfural	2.8
3-Methyl -2-cyclopenten-1-one	0.4
2,3-Dimethylcyclopent-2-en-1-one	0.3
Propionic acid	2.1
Butylolactone	0.4
Butanoic acid	0.9
Pentanoic acid	0.5
2-Hydroxy-3-methyl-2-cyclopenten-1-one	0.6
Guaiacol	1.6
Pentenoic acid	0.1
3-Ethyl-2-hydroxy-2-cyclopenten-1-one	0.1
4-Methyl-guaiacol	0.4
Phenol	35.8
4-Ethyl-guaiacol	0.2
p-Cresol	0.6
m-Cresol	0.6
4-Ethyl-phenol	0.3
Syringol	1.0
3-Pyridinol	0.2
Unknown compounds	3.0

4.   CONCLUSION

Carbonization or slow pyrolysis of biomass yields char as the main product. Previous studies on slow pyrolysis of EFB, OPF and OPT or other biomass have shown that the terminal temperature is the major factor affecting product yields. In this study, slow pyrolysis of OPS was done in a small industrial scale pyrolyser with external slow heating to a terminal pyrolysis temperature of about 600 °C. The solid product and condensates were analysed to determine their compositions and qualities.

The main product of OPS char with 83.30% fixed carbon, an energy content of 30.83 MJ kg^{-1} and little ash was obtainable from the industrial scale pyrolyser. OPS char has multiple uses such as for fuel, soil enrichment and conversion into activated carbon.

The condensates separated into two fractions: a tarry and an aqueous fraction. The tarry fraction was analysed by FT-IR and it was found to be a complex mixture, highly-oxygenated with a great amount of large molecules, which involve nearly all species of oxygenated organics, such as esters, ethers, aldehydes, ketones, phenols, carboxylic acids and alcohols. Therefore it can be a source of different ketones and acidic compounds as well as phenolic compounds if proper extraction processes are adopted for the recovery of these chemicals. The OPS oil is also a potential bio-oil with an energy content of 32.44 MJ kg^{-1}. OPS vinegar may be applied as wood vinegar, which has traditionally been used as an insect repellent, deodorizer, antibacterial agent, sterilizer, alkaline bath and wash, cosmetic and food additive. Many more new uses of the liquid products are still being explored.

The gaseous products which were non-condensable were not investigated. However they are combustible and thus can also be used as a fuel.

carried out the GC-MS analysis of the OPS vinegar at the Laboratory of Biomass Chemistry.

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