Characterisation of oil palm trunk and frond as fuel for biomass thermochemical

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Abstract. The rate of oil palm production in Malaysia increases annually and as a result, the oil palm wastes, especially oil palm trunk (OPT) and oil palm fronds (OPF) remain abundant. A suitable way of converting this abundant waste to renewable energy is through thermochemical conversion. Thus, this study investigates the characteristics of OPT and OPF biomass, for use as feedstock in thermochemical processes like gasification, pyrolysis, and combustion. The analysis carried out includes: ultimate (CHNSO) and proximate (thermogravimetric) analysis, calorific value, field emission scanning electron microscopy (FESEM) and x-ray fluorescence (XRF). Both feedstocks exhibited potential for use as fuel in biomass thermochemical conversion. The CHNSO analysis showed the presence of sufficient carbon, hydrogen and oxygen elements in both feedstocks, with carbon being the highest 45.42% in OPT and 43.35% in OPF. The percentages of nitrogen and sulphur which are required to be less for a good fuel were also obtained in low quantities for both fuel; 0.47% and 0.13% in OPT and 0.76% and 0.45% in OPF, respectively. The thermogravimetric analysis revealed both feedstocks to be having high volatile matter 62.28% in OPT and 66.10% in OPF. Meanwhile, sufficient fixed carbon content of 26.18% in OPT and 25.68% in OPF with low ash content of 9.82% in OPT and 6.32% in OPF were obtained in the analysis. FESEM and XRF were used to investigate the surface morphology, elemental and mineralogical nature of the samples. The findings were compared with those of other biomass and non-biomass materials. The EDX graph showed the presence of carbon and oxygen in a higher amount while in the XRF analysis CaO and K2O were the major oxides present in both OPT and OPF, with a low amount of SiO making the feedstocks less prone to agglomeration during thermochemical conversion.

1. Introduction
Global concerns on the depletion of fossil fuels and the need for cleaner energy and safer environment are rekindling researcher’s efforts on the lookout for more renewable energy resources that can be utilised. Among the renewable energy sources, biomass is considered an excellent option due to its abundance. Thermochemical processes like liquefaction, combustion, pyrolysis, and gasification have proven to be an effective means of biomass energy conversion [1]. It is desirable to partake characterisation tests to ascertain the suitability of using biomass feedstock as fuel for energy generation. The oil palm tree is considered as one of the major biomass sources in Malaysia, and the country happens to be amongst the world’s largest producers of palm oil, with an increasing plantation area reported as 5.23 million hectares in 2013, 5.39 million hectares in 2014, 5.64 million hectares in 2015, and 5.74 million hectares in 2016. The oil palm planted area in 2017 reached 5.81 million hectares...
hectares, an increase of 1.3% as against that of the previous year. Sarawak overtook Sabah as the largest oil palm planted state, with 1.56 million hectares or 26.8% of the total Malaysian oil palm planted area, followed by Sabah with 1.55 million hectares or 26.6% and Peninsular Malaysia with 2.70 million hectares or 46.6% [2]. Recent concerns on accelerating replanting activity, improving oil extraction rate, expanding mill capacity, etc. are expected to further increase the total oil palm biomass availability in Malaysia. This situation has presented a huge opportunity for the utilization of the oil palm biomass in various applications including renewable energy [3].

The major parts of the oil palm tree utilised as biomass sources include the oil palm frond (OPF), empty fruit bunch (EFB), palm kernel shell (PKS) and oil palm trunk (OPT). This study focused on OPF and OPT, the OPF is usually available throughout the year during the pruning, or fruits harvesting period while OPT is only available in abundance during replanting periods. The Malaysian oil palm sector produces approximately 80 million dry tonnes of solid biomass, which contributes to 85.5% of the total dry biomass share in the country [4-6]. Generally, oil palm mills generate several oil palm wastes. The oil palm wastes contribute about RM6379 millions of energy annually [7]. However, more effort is needed to optimise the utilization of oil palm wastes for cogeneration in Malaysia. The knowledge of the characteristics of such biomass is of immense importance to determine their feasibility for use in thermochemical processes or as raw materials for use in industries. The elemental study of biomass helps to point out the levels of inorganic elements that may be released during the thermal processing of the biomass [8]. This information helps in the modelling, analysis, and designing of energy conversion processes along with the prediction of the economic feasibility of establishing such gasification systems. This study intends to characterise OPT and OPF for use as feedstock in thermochemical processes through processes that include proximate and ultimate analysis, calorific value, and elemental analysis.

2. Methodology

2.1. Sample preparation

The OPT and OPF samples were obtained from Felcra plantation, Bota Kanan Perak, Malaysia as shown in figure 1. The samples were collected as replanting exercise was going on in the plantation. The samples were collected raw from the site, and size reduction for proper drying was immediately carried out. The samples were oven-dried immediately at a temperature of 105 °C for 24 hours to remove excess moisture and were later sun-dried for 6 hrs, for ten days. The dried samples were later granulated, after which they were ground again and sieved to a particle size of 250 µm as depicted by figure 2.

![Figure 1. Images of (a) oil palm frond and (b) oil palm trunk in drying process.](image-url)
Figure 2. Ground and sieved samples of (a) OPT and (b) OPF.

2.2 Characterisation methods

The heating value of a material can be expressed in either lower (LHV) or higher heating value (HHV). The former is obtained when the heat of the combustion of the sample was determined relative to gaseous water while the latter is obtained when the product of the heat of combustion of the sample was determined relative to liquid water. The between the two values gives the latent heat of the product water \[9\]. In the given study, the Leco AC-350 bomb calorimeter was used for the determination of heating values.

The CHNSO elemental analysis determines the basic composition of a feedstock in terms of the percentage proportion of carbon (C), hydrogen (H), nitrogen (N), sulfur (S) oxygen (O) and ash in order to establish its suitability for energy production and for the calculation of stoichiometric air to fuel ratio \[10\]. The analysis was conducted according to the ASTM D3176-15 standard by using a Leco CHNS-932 model analyser. The weight percentage of carbon, hydrogen, nitrogen, and sulphur were reported directly from the analysis and oxygen was determined by difference \[11\]. The ash value was obtained from the thermogravimetric analysis. The thermogravimetric analysis is used to determine the amount of moisture content (M), volatile matter (VM), ash (A) and fixed carbon content (FC) present in the feedstock. In this study, the analysis was carried out using a TGA analyser (Pyris -1 TGA) based on ASTM E 1131-98 standard test method for compositional analysis by thermogravimetry. Thermogravimetric analysis is an empirical technique in which the mass of a substance is heated at a controlled rate and the weight loss is recorded as a function of temperature and time \[12\].

FESEM microstructures, EDX analysis, and XRF analysis were used in this study to determine the elemental distribution and composition of OPT and OPF. The microstructure of each sample was determined using a field emission scanning electron microscope (FESEM) at different magnifications. The weight percentage of each element was determined using energy dispersive X-ray spectroscopy (EDX). The XRF analysis was used to determine the inorganic composition of the biomass samples, SUPRA 55VP model Field Emission Scanning Electron Microscopes (FESEM) analyser in combination with Energy Dispersive X-ray Spectroscopy (EDS) in non-conducting specimens mode was used.

3. Results and discussion

3.1. Calorific value

The amount of heat energy released from the combustion of the sample is proportional to the heating value of the material or calorific value. The higher a fuel heating value the higher the energy that will be dissipated during combustion and as such for thermal conversion purposes, fuels with high calorific
value are more desirable. Table 1 tabulates the calorific value of OPT and OPF along with some selected biomass, coal and plastics. The range of calorific value of biomass feedstocks is given between 15-20 MJ/kg [8]. The oil palm trunk and frond have a calorific value of 17.41 MJ/kg and 17.48 MJ/kg which falls within that range and is also very similar to other biomass like the date palm frond, empty fruit bunch, rice husk and cotton stalk. The calorific value of the plastic feedstock is seen to be higher than that of both OPT and OPF which may be due to the difference in chemical composition. Nevertheless, the calorific values of OPT and OPF were found to be nearly similar to peat and lignite coal confirming to their potential for use as both domestic and industrial fuel.

Table 1. Calorific value of OPT and OPF and some selected coal, biomass and plastic types.

| Type       | Sample                  | Calorific value (MJ/kg) | Ref       |
|------------|-------------------------|-------------------------|-----------|
| Coal       | Peat                    | 14                      | [13]      |
|            | Lignite                 | 16.3                    | [11]      |
|            | Bituminous              | 23.25                   | [11]      |
| Biomass    | Redwood waste wood      | 21.29                   | [6]       |
|            | OPF                     | 17.28                   | [5]       |
|            | OPF                     | 17.48                   | Current study |
|            | Rice husk               | 14.79                   | [13]      |
|            | Wheat straw             | 16.59                   | [14]      |
|            | Municipal waste         | 19.83                   | [6]       |
|            | Animal waste            | 17.10                   | [6]       |
|            | Oil palm trunk          | 17.41                   | Current study |
|            | Date palm frond         | 17.57                   | [12]      |
|            | Empty Fruit bunch       | 18.60                   | [11]      |
|            | Saw dust pellet         | 20.45                   | [11]      |
|            | Sugar cane bagasse      | 15.25                   | [13]      |
|            | Cotton stalk            | 18.26                   | [11]      |
| Plastics   | Polyethylene            | 43.00                   | [14]      |
|            | Mixed Plastic           | 35.00                   | [14]      |
|            | PVC                     | 22.90                   | [15]      |
|            | Polystyrene             | 38.60                   | [15]      |

3.2. CHNSO elemental analysis
The CHNSO elemental analysis was conducted using a Leco-932 analyser and the values of C, H, N, S were determined directly from the result. The value of oxygen was determined by the difference method. Table 2 shows the analysis result for OPT and OPF, and other biomasses found from the literature for comparison. The CHNSO elemental analysis showed the presences of high carbon content in both OPT and OPF which was comparable to that of the low-rank coal. The carbon contents were also similar to most forestry biomass and agricultural biomass. The level of nitrogen and sulphur which may cause environmental effect is seen less in both OPT and OPF as compared to other biomass and is seen as negligible compared to that of coal.
Table 2. CHSNO elemental analysis of OPT, OPF and other feedstock.

| Material            | C   | H   | N   | S   | O   | Reference |
|---------------------|-----|-----|-----|-----|-----|-----------|
| Peat                | 55  | 6   | 0.38| 0.25| 35  | [13]      |
| Lignite             | 50  | 4   | 2   | 0.90| 43.1| [13, 16]  |
| Bituminous          | 68  | 4   | 3   | 0.90| 24.10| [13, 16] |
| Date palm frond     | 40.48| 5.63| 0.28| 0.00| 53.61| [17]      |
| Corn stover         | 43.65| 5.56| 0.61| 0.01| 50.17| [16]      |
| Rice husk           | 38.74| 5.83| 0.55| 0.06| 54.82| [18]      |
| Wheat straw         | 42.11| 6.53| 0.58| 0.32| 40.51| [16]      |
| Sesame stalk        | 41.34| 6.57| 0.81| 0.29| 45.16| [19]      |
| OPF                 | 44.58| 4.53| 0.71| 0.07| 48.80| [8]       |
| OPF                 | 45.42| 6.35| 0.47| 0.13| 47.63| Current study |
| OPT                 | 43.35| 6.26| 0.76| 0.45| 49.18| Current study |
| Empty fruit bunch   | 40.73| 5.75| 1.40| 0.22| 51.90| [18]      |
| Palm kernel shell   | 49.65| 6.13| 0.41| 0.48| 43.33| [18]      |
| Sugarcane bagasse   | 42.93| 5.82| 0.68| 0.06| 54.82| [18]      |
| Coconut shell       | 43.00| 6.30| 0.75| 0.05| 49.90| [18]      |

3.3. Thermogravimetric analysis

The proximate analysis result of OPF and OPT is given in table 3 with that of other biomass and coal types. The weight loss with a change in temperature of the two biomasses is shown in figure 3.

Table 3. Thermogravimetric analysis of OPT and OPF samples and some selected biomass and coal.

| Sample             | Volatile matter | Fixed Carbon | Ash   | Reference |
|--------------------|-----------------|--------------|-------|-----------|
| Peat               | 65              | 26.5         | 8.5   | [13]      |
| Lignite            | 34.41           | 48.39        | 17.2  | [16]      |
| Bituminous         | 18.69           | 61.86        | 19.63 | [16]      |
| OPT                | 62.28           | 26.18        | 9.82  | Present study |
| OPF                | 66.10           | 25.68        | 6.32  | Present study |
| Coconut shell      | 78              | 19.48        | 5.52  | [18]      |
| Corn stover        | 75.17           | 19.25        | 5.58  | [16]      |
| Sesame Stalk       | 72.2            | 17.0         | 6.6   | [19]      |
| Rice Husk          | 72.2            | 12.0         | 15.8  | [18]      |
| Sugar cane bagasse | 80.19           | 15.91        | 3.9   | [18]      |
| Red wood           | 83.5            | 16.1         | 0.4   | [12]      |

From the results, comparing OPF and OPT with the other biomass it is seen that the volatile and fixed carbon contents are within the range of the other biomass, though the amount of volatile matter and fixed carbon present in OPF is quiet higher than OPT. Conversely, OPT has more ash content than OPF which indicates the need for ash handling during gasification of OPT, noting that rice husk and the coal types have more ash content than the OPT.
3.4. EDX analysis
The microstructure of each sample is shown in figures 4 to 6, as determined by field emission scanning electron microscope (FESEM). The weight percentage of each element was determined using energy dispersive X-ray spectroscopy (EDX) as shown in table 4.

![Figure 4](image_url)

(a) FESEM image and (b) EDX spectrum of raw OPT.
Figure 5. (a) FESEM image (b) EDX spectrum of raw OPF.

Figure 6. (a) FESEM image (b) EDX spectrum of Raw Rice Husk [8].

Table 4. EDX result for OPT and OPF raw samples.

| Elements | OPT Weight% | Atomic% | Weight% | Atomic% | Weight% | Atomic% |
|----------|-------------|---------|---------|---------|---------|---------|
| C        | 53.86       | 61.32   | 53.39   | 61.77   | 32.21   | 42.51   |
| O        | 44.20       | 37.79   | 42.09   | 36.55   | 45.40   | 49.98   |
| Cl       | -           | -       | 2.18    | 0.85    | -       | -       |
| K        | 0.4         | 0.14    | 1.72    | 0.61    | 0.77    | 0.31    |
| Ca       | -           | -       | 0.62    | 0.21    | -       | -       |
| Na       | -           | -       | -       | -       | -       | -       |
| Mg       | -           | -       | -       | -       | -       | -       |
| Si       | 1.54        | 0.75    | -       | -       | 21.62   | 12.20   |

The carbon weight obtained from EDX for both OPT and OPF was higher than that obtained from the ultimate analysis. The EDX analysis predicted the carbon content of OPT to be 53.86% and that of OPF to be 53.39% while from the ultimate analysis the carbon content was 43.35% and 45.42% for OPT and OPF respectively. This may be because of the untraced hydrogen and nitrogen in EDX analysis. It is of immense importance to consider the presence of inorganic elements like Al, Na, K, Si, Mg and Ca present in the biomass samples as they have to be considered in the design of
thermochemical processing systems. The high contents of such elements may lead to critical problems during the gasification process operation. From table 3, the OPT contains very little amount of K, 0.4% so also the rice husk with 0.77% while that of OPF was quiet higher being 1.72%. It is noteworthy that potassium form salts with different elements and may cause corrosion and erosion problems in the gasification process on the downstream equipment. The presence of Ca is not seen in OPT and rice husk, but in the case of OPF, it has about 0.62%. The Si content in OPT is relatively negligible (1.54%) compared to the one present in rice husk, while in the case of OPF there was no trace of it. However silicon content as low as 1% may lead to problems during the combustion of biomass due to the production of slagging in silicates form [20]. A high amount of Si present in the rice husk about 21.62% suggests that using the rice husk for the gasification process may require ash handling and syngas cleaning systems. Usually, non-woody biomass has a high amount of silicon compared to woody biomass [21].

From the XRF result in table 5, CaO and K2O form part of the major oxides found in both OPT and OPF constituting 18.7% and 36.5% CaO, 44.5% and 32.1% K2O respectively. The CaO level in rice husk (3.13%) and wheat straw (3.12%) is less compared to that present in OPT, OPF and wood ash (39.03%), while the K2O for wood ash (13.34%) and wheat straw (18.85%) are quiet higher compared to that found in rice husk (8.78%). The amount of silicon oxide is highest in rice husk about 73.20%, then wheat straw 65.45% with lower levels found in OPT, OPF and, wood. The higher amount of K2O and SiO present in a feedstock might the result into the formation of a compound K2O-SiO which may accelerate agglomeration problem [22]. However, the presence of bed materials like Al2O3, MgO, CaO, Fe2O3 reduces such problems by forming a high-temperature compound. Therefore the high content of CaO in OPF and wood ash may help to suppress agglomeration problems than in rice husk and wheat straw making them less preferable for gasification process. As for OPT, the presence of Fe2O3 oxide in conjunction with the CaO will also hinder agglomeration during the gasification.

**Table 5.** XRF Analysis of OPT, OPF and Rice Husk.

| Oxides       | Current Result | Literature Results [8] |
|--------------|----------------|------------------------|
|              | OPT | OPF | Rice Husk | Wood Ash | Wheat Straw |
| CaO          | 18.7 | 36.5 | 3.14 | 39.03 | 3.12 |
| K2O          | 44.5 | 32.1 | 8.78 | 13.34 | 18.85 |
| Cl           | 6.65 | 15.2 | 2.38 | 0.06 | 3.58 |
| P2O5         | 5.37 | 4.45 | 7.55 | 3.85 | 1.17 |
| SiO2         | 8.33 | 4.33 | 73.20 | 11.72 | 65.45 |
| SO3          | 8.30 | 1.95 | 3.35 | - | - |
| MgO          | 1.15 | 1.93 | 0.91 | 6.03 | 2.10 |
| Fe2O3        | 4.82 | 1.90 | 0.32 | 1.32 | 0.44 |
| MnO          | 0.451 | 1.23 | 0.31 | 6.03 | 0.08 |
| NiO          | 0.397 | 0.147 | - | - | - |
| CuO          | 0.114 | 0.111 | 0.04 | - | - |
| ZnO          | 0.215 | 0.110 | 0.05 | - | - |
| Pd           | 0.07 | 0.0860 | - | - | - |
| Rb2O         | 0.169 | 0.0109 | - | - | - |

**4. Conclusion**

Oil palm trunk and frond have been characterised for use in thermochemical processes like gasification and combustion. The ultimate analysis showed that OPT and OPF had a carbon content of 43.35% and 45.42% respectively. The heating value analysis exhibited their potential for use as solid fuels as their calorific values 17.41 MJ/kg and 17.48 MJ/kg lies within the biomass calorific value range and was closely similar to that of low-rank coals. The proximate analysis indicated fewer ash contents in the samples with OPT having higher amount 9.82% than OPF 6.32%. From the elemental analysis, the
EDX result exhibited a higher amount of carbon for both OPT and OPF, in the XRF result, the presence of CaO and K2O in high levels were detected for both samples. The presence of SiO in small traces in both feedstocks might lead to agglomeration. However, the presence of high CaO present in OPF may dampen the process to form a high-temperature compound. Also in the case of OPT, the CaO and Fe2O3 present will counter the effect of agglomeration. Overall OPT and OPF have exhibited remarkable properties for use in thermochemical conversion as they have sufficient C, H, O content, high calorific value and volatile matter, and low ash content and less prone to sintering and agglomeration. This makes OPT and OPF a suitable feedstock for power generation in processes like gasification, combustion, and pyrolysis.

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