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# Estimation of Higher Heating Value of Torrefied Palm Oil Wastes from Proximate Analysis

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## Abstract

In Malaysia, palm oil wastes are identified as the potential biomass for renewable energy sources. Usually the higher heating value (HHV) is essential for energy analysis and can be estimated using bomb calorimeter but this method usually is time consuming with possibilities of experimental errors. Thus many correlations have been established to predict the HHV based on the proximate analysis. However, most of the correlations only take into account the HHV of raw biomass. No attempts have been made on estimating HHV of torrefied biomass using model correlation. Therefore, the objective of this study is to propose new correlation based on proximate analysis which is applicable for raw and torrefied palm oil wastes. The HHV and proximate analysis of raw and torrefied palm oil wastes at different torrefaction temperature ranges from 240 to 330°C are measured experimentally for model correlation. In addition the HHV and proximate analysis of raw and torrefied palm oil wastes from published literature are included in order to enhance the reliability of model correlation. Based on the model correlation, low average absolute error (AAE) of 5.37% and low average bias error (ABE) of -1.00% are obtained indicating the estimated model correlation is suitable and reliable to estimate the HHV of raw and torrefied palm oil wastes from proximate analysis.

*Keywords:* Torrefaction; Correlations; Palm Oil Wastes; Proximate Analysis; Higher Heating Value

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## 1. Introduction

Wastes from oil palm mill and plantation are consisting of empty fruit bunch (EFB), palm kernel shell (PKS), palm mesocarp fibre (PMF), oil palm frond (OPF) and oil palm trunk (OPT) are feasible to be used as a source of renewable energy. In 2013, according to Uemura et al., Malaysia roughly need an energy supply of 70 Mtoe (millions tons of oil equivalent) and palm oil wastes have the potential to contribute 17 Mtoe thus decrease the use of fossil fuels [1]. Malaysia as the world second producer of palm oil in 2015 indicates that there are abundant of palm oil wastes that can be utilized as important energy source [1]. However, utilizing palm oil waste as renewable energy source requires the needs to study its physical, chemical and thermodynamics properties.

High heating value (HHV) is an important property of a fuel as a measure of energy content. Bomb calorimeter is usually used to determine the HHV of a fuel. This method of determining HHV is sophisticated, expensive and prone to errors. In order to avoid such difficulties, correlations have been developed to estimate the HHV of biomass by using proximate and ultimate analysis. The methods for estimating HHV dates back to the late 1800s where the first correlation is introduced based on the ultimate properties of coal [2]. Ultimate analysis gives elemental composition of biomass and needs special arrangement of the experimentation. Meanwhile proximate analysis gives the information of fixed carbon, volatile matter and ash content of the biomass and the method is relatively simple and cheap compare to ultimate analysis. That is why the popularity of estimating HHV using proximate analysis is on the rise. However the estimated HHV from published correlations only consider the raw condition of biomass and not the torrefied conditions. Although the published correlations [3-5] cover wide ranges of biomass from various country, it does not guarantee the accuracy of HHV for torrefied biomass. Using established correlations to estimate the HHV of torrefied biomass often yields a significance error when compare to the measured HHV. In addition, palm oil wastes data are usually not included as part of the biomass database in the most correlations development and thus limiting the correlations capability [3-5].

The objective of this study is to propose a new correlations to estimate the HHV of raw and torrefied palm oil wastes. The palm oil wastes used in this study are EFB, PKS, PMF and OPF. The HHV and proximate analysis for raw and torrefied palm oil wastes at temperatures of 240, 270, 300 and 330°C are used in this work. In addition the HHV and proximate analysis for raw and torrefied palm oil wastes obtained from published literature are also included during the model correlation to enhance the model reliability. 15 correlation models are used for estimating the HHV using proximate analysis where the best correlation model is selected based on the lowest average absolute error (AAE) and average bias error (ABE). In addition performance comparison between the proposed correlation and published correlation is also highlighted.

## 2. Methodology

The database for proximate analysis and the experimental HHV of the palm oil wastes were obtained from experimental work performed in this study and published literature as shown in Table 1. In order to ensure that the model can be used for raw and torrefied palm oil wastes, 40 sets of data from previous studies entirely from Malaysia have been included in the database. From 40 sets of data, it can be seen that the volatile matter (VM), fixed carbon (FC) and ash content are in the ranges of 6.00-79.37%, 9.57-84.86% and 0.2-25.60% respectively.

In this study, 15 correlations are proposed as shown in Table 2. In the all correlation, 2 new variables are introduced which are the residence time (t) and temperature (T). Therefore the HHV for raw and torrefied palm oil wastes can be predicted using the same correlation. In order to calculate the HHV using proximate analysis data, the unknowns of a, b, c, d, e and f in Table 2 are estimated by using Microsoft Excel Solver Tool for all correlations.

Table 1. Composition of proximate analysis and higher heating value of raw and torrefied oil palm waste

| No | Biomass | Residence time (min) | Torrefaction temperature (°C) | Proximate analysis (wt.%) | | | Experimental HHV (MJ/kg) | Sources |
|---|---|---|---|---|---|---|---|---|
| | | | | FC | VM | Ash | | |
| Raw biomass | | | | | | | | |
| 1 | Oil palm frond | | | 12.01 | 69.17 | 2.87 | 17.75 | This study |
| 2 | Oil palm frond | | | 79.37 | 20.63 | 25.60 | 17.67 | [6] |
| 3 | Palm kernel shell | | | 12.07 | 70.02 | 6.04 | 16.15 | This study |
| 4 | Palm kernel shell | | | 15.15 | 73.77 | 11.08 | 16.30 | [7] |
| 5 | Palm kernel shell | | | 18.70 | 70.50 | 0.84 | 20.10 | [8] |
| 6 | Palm kernel shell | | | 23.00 | 74.00 | 3.00 | 17.58 | [9] |
| 7 | Palm kernel shell | | | 19.70 | 67.20 | 2.10 | 16.41 | [10] |
| 8 | Palm kernel shell | | | 10.85 | 84.86 | 4.29 | 18.81 | [11] |
| 9 | Empty fruit bunch | | | 15.37 | 65.01 | 3.85 | 15.49 | This study |
| 10 | Empty fruit bunch | | | 16.80 | 77.10 | 6.10 | 16.80 | [10] |
| 11 | Palm mesocarp fiber | | | 16.42 | 67.04 | 5.66 | 16.94 | This study |
| 12 | Palm mesocarp fiber | | | 19.72 | 9.57 | 9.57 | 16.63 | [12] |
| 13 | Palm mesocarp fiber | | | 20.51 | 72.46 | 7.03 | 17.13 | [13] |
| Torrefied biomass | | | | | | | | |
| 14 | Oil palm frond | 30 | 240 | 22.18 | 64.86 | 3.20 | 19.82 | This study |
| 15 | Oil palm frond | 30 | 270 | 32.44 | 56.15 | 4.62 | 21.60 | This study |
| 16 | Oil palm frond | 30 | 300 | 44.88 | 45.54 | 4.76 | 23.79 | This study |
| 17 | Oil palm frond | 30 | 330 | 52.05 | 38.95 | 5.15 | 25.83 | This study |
| 18 | Palm kernel shell | 30 | 240 | 21.85 | 66.27 | 7.28 | 19.68 | This study |
| 19 | Palm kernel shell | 30 | 270 | 23.85 | 65.70 | 8.13 | 21.91 | This study |
| 20 | Palm kernel shell | 30 | 300 | 28.29 | 58.55 | 12.11 | 23.64 | This study |
| 21 | Palm kernel shell | 30 | 330 | 35.83 | 49.68 | 13.71 | 25.46 | This study |
| 22 | Palm kernel shell | 30 | 240 | 19.77 | 74.56 | 4.89 | 19.70 | [9] |
| 23 | Palm kernel shell | 30 | 260 | 22.04 | 73.77 | 6.21 | 19.72 | [9] |
| 24 | Palm kernel shell | 30 | 280 | 21.25 | 75.15 | 5.62 | 19.86 | [9] |
| 25 | Palm kernel shell | 60 | 240 | 21.06 | 73.66 | 6.37 | 20.35 | [9] |
| 26 | Palm kernel shell | 60 | 260 | 22.83 | 70.84 | 6.82 | 21.09 | [9] |
| 27 | Palm kernel shell | 60 | 280 | 20.51 | 73.63 | 6.69 | 20.59 | [9] |
| 28 | Palm mesocarp fiber | 30 | 240 | 19.05 | 66.07 | 6.08 | 18.05 | This study |
| 29 | Palm mesocarp fiber | 30 | 270 | 23.02 | 64.60 | 6.67 | 19.17 | This study |
| 30 | Palm mesocarp fiber | 30 | 300 | 29.69 | 59.58 | 7.10 | 21.49 | This study |
| 31 | Palm mesocarp fiber | 30 | 330 | 33.86 | 56.43 | 8.16 | 22.91 | This study |
| 32 | Palm mesocarp fiber | 60 | 250 | 27.30 | 63.90 | 8.90 | 20.10 | [14] |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 33 | Palm mesocarp fiber | 60 | 275 | 32.40 | 56.60 | 11.00 | 21.40 | [14] |
| 34 | Palm mesocarp fiber | 60 | 300 | 44.40 | 41.30 | 14.30 | 23.40 | [14] |
| 35 | Palm mesocarp fiber | 60 | 325 | 52.40 | 32.80 | 14.80 | 23.70 | [14] |
| 36 | Palm mesocarp fiber | 60 | 350 | 55.30 | 29.10 | 15.50 | 23.90 | [14] |
| 37 | Empty fruit bunch | 30 | 240 | 22.06 | 62.51 | 6.70 | 15.59 | This study |
| 38 | Empty fruit bunch | 30 | 270 | 30.16 | 54.50 | 7.67 | 17.99 | This study |
| 39 | Empty fruit bunch | 30 | 300 | 39.23 | 48.44 | 7.70 | 19.60 | This study |
| 40 | Empty fruit bunch | 30 | 330 | 48.91 | 36.63 | 11.88 | 22.07 | This study |

Table 2. Proposed correlations used in this study

| **No** | **Proximate analysis** |
|---|---|
| **1** | HHV = a + bFC/VM + cVM/FC + dt/T |
| **2** | HHV = a + bFC/VM + cVM/FC + dt + e/T |
| **3** | HHV = a + bFC/VM + cVM/FC + dt + eT |
| **4** | HHV = a + bFC/VM + cVM/ASH + dt/T |
| **5** | HHV = a + bFC/VM + cVM/ASH + dt + e/T |
| **6** | HHV = a + bFC/VM + cVM/ASH + dt + eT |
| **7** | HHV = a + bASH/FC + cFC/VM + dt/T |
| **8** | HHV = a + bASH/FC + cFC/VM + dt + e/T |
| **9** | HHV = a + bASH/FC + cFC/VM + dt + eT |
| **10** | HHV = a + bFC/VM + cVM/ASH + dASH/FC + et/T |
| **11** | HHV = a + bFC/VM + cVM/ASH + dASH/FC + et + f/T |
| **12** | HHV = a + bFC/VM + cVM/ASH + dASH/FC + et + fT |
| **13** | HHV = a + bVM/FC + cASH/VM + dFC/ASH + et/T |
| **14** | HHV = a + bVM/FC + cASH/VM + dFC/ASH + et + f/T |
| **15** | HHV = a + bVM/FC + cASH/VM + dFC/ASH + et + fT |

The best correlation is selected based on the lowest average absolute error (AAE) and average bias error (ABE) which can be calculated using Eqs. (1) and (2). The lowest value of error indicates that the correlations estimate the value of HHV close to the experimental HHV. For average bias error, the positive number indicates that the correlation overestimated the HHV value while negative value means an underestimate of HHV value. Whether it is positive of negative value, the closer the error to the zero then the more accurate the correlations.

$$Average\ \ Absolute\ \ Error\,(AAE) = \sum_{i=1}^{N}\left(\frac{Estimated\ HHV\ value - Experimental\ HHV\ value}{Experimental\ HHV\ value}\right)\times 100\% \Big/ N \tag{1}$$

$$Average\ \ Bias\ \ Error\,(ABE) = \sum_{i=1}^{N}\left(\frac{Estimated\ HHV\ value - Experimental\ HHV\ value}{Experimental\ HHV\ value}\right)\times 100\% \Big/ N \tag{2}$$

## 3. Results and discussion

The predicted values for the unknowns of a, b, c, d, e and f for all 15 correlations are shown in Table 3. It can be seen that by using the data from Table 1, correlation no. 12 shows the lowest AAE of 5.37 %**.** Although the ABE error is -1.00% which is not the lowest, it is still in the acceptable range. The lowest AAE indicates that the correlation no. 12 is able to estimate the HHV of raw and torrefied palm oil wastes very close to the HHV obtained from experimental. The correlation no. 12 also shows the types of linear equation particularly the variables of residence time and torrefaction temperature. This is absolutely true because the HHV tends to increase linearly as the residence times and torrefaction temperatures are increased [15].

Table 3. Linear correlations of palm oil wastes

| No | Correlations | AAE (%) | ABE (%) |
|---|---|---|---|
| Linear correlations | | | |
| **1** | HHV = 17.0706 + 2.8114FC/VM – 0.0389VM/FC + 13.9831t/T | 6.46 | -0.53 |
| **2** | HHV = 18.3388 + 2.4520FC/VM – 0.0489VM/FC + 0.0308t – 30.1360/T | 6.07 | -0.02 |
| **3** | HHV = 16.6574 + 1.9543FC/VM – 0.0131VM/FC + 0.0350t + 0.056T | 5.76 | -0.93 |
| **4** | HHV = 15.7390 + 3.5006FC/VM + 0.0409VM/ASH + 16.4264t/T | 6.14 | -1.45 |
| **5** | HHV = 18.1825 + 2.8670FC/VM – 0.0008VM/ASH + 0.0293t – 50.0520/T | 5.91 | -1.02 |
| **6** | HHV = 15.8104 + 2.4104FC/VM + 0.0413VM/ASH + 0.0300t + 0.0066T | 5.42 | -1.06 |
| **7** | HHV = 17.2686 – 0.2497ASH/FC + 2.7501FC/VM + 13.0299dt/T | 6.48 | 0.14 |
| **8** | HHV = 18.3740 – 0.2930ASH/FC + 2.2093FC/VM + 0.0298t – 25.3865/T | 6.17 | 0.18 |
| **9** | HHV = 16.3218 + 0.0364ASH/FC + 2.0316FC/VM + 0.0248t + 0.0081T | 5.62 | -1.13 |
| 10 | HHV = 15.5247 + 3.7767FC/VM + 0.0424VM/ASH + 0.2845ASH/FC + 16.2336t/T | 6.06 | -1.32 |
| 11 | HHV = 18.2442 + 3.3482FC/VM + 0.0421VM/ASH + 0.2477ASH/FC + 0.0053t – 69.7405/T | 5.69 | -0.89 |
| **12** | **HHV = 15.8514 + 1.9293FC/VM + 0.0418VM/ASH + 0.1398ASH/FC + 0.0234t + 0.0082T** | **5.37** | **-1.00** |
| **13** | HHV = 16.1455 – 0.0632VM/FC + 6.3680ASH/VM + 0.1850FC/ASH + 16.4289t/T | 6.62 | -2.82 |
| **14** | HHV = 17.6915 – 0.0664VM/FC + 6.7218ASH/VM + 0.1870FC/ASH + 0.0415t – 42.8253/T | 5.68 | -0.58 |
| **15** | HHV = 15.7306 – 0.0579VM/FC + 6.4294ASH/VM + 0.1877FC/ASH – 0.0037t + 0.0124T | 5.53 | -0.98 |

Fig. 1 shows the comparison between estimated and experimental HHV using the proposed correlation. Most of the estimated HHV remain close to the line $HHV_{estimated} = HHV_{experimental}$, indicating a good accuracy for the proposed correlation.

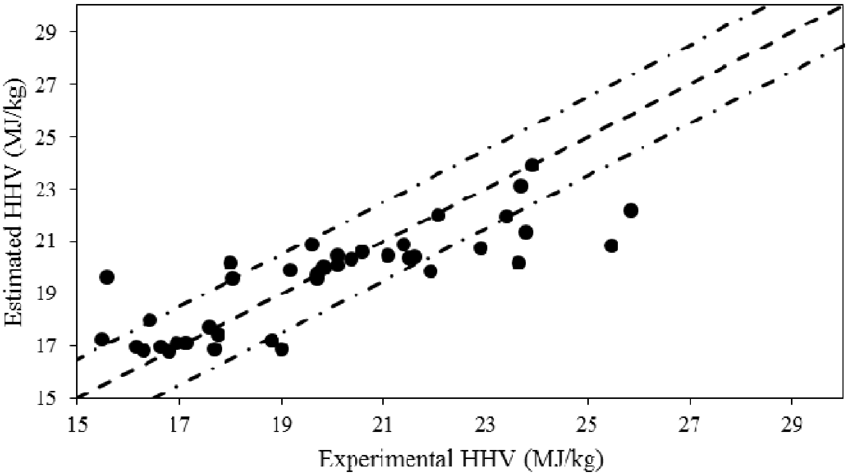

Fig. 1. Comparison between estimated and experimental HHV for the proposed correlation

The obtained correlations are then compared with the established correlations by using the same data in Table 1. The errors for each correlation are presented in Table 4. It shows that the correlation used in this study predicted accurately compared to the established correlations. This may be due to the specific category of biomass (palm oil wastes) group chosen in this study. Most of the established correlations utilized various group of biomass during their model correlation development and only the HHV and proximate analysis of raw biomass are used for HHV estimation thus limiting its applicability into specific range of group of biomass and for raw biomass only.

Table 4. Comparison with the other established correlations

| **Correlations** | **Sources** | **AAE (%)** | **ABE (%)** |
|---|---|---|---|
| **$HHV = 15.8514 + 1.9293FC/VM + 0.0418VM/ASH + 0.1398ASH/FC + 0.0234t + 0.0082T$** | **This study** | **5.37** | **-1.00** |
| $HHV = 0.3536FC + 0.1559VM - 0.0078ASH$ | [4] | 7.82 | -3.30 |
| $HHV = 0.1905VM + 0.2521FC$ | [5] | 9.46 | -4.91 |
| $HHV = 19.2880 - 0.2135VM/FC - 1.9584ASH/VM + 0.0234FC/ASH$ | [3] | 11.09 | -5.42 |

## 4. Conclusions

The model correlation for estimating the HHV for raw and torrefied palm oil wastes has been developed in this work. 40 sets of palm oil wastes data including HHV and proximate analysis have been included in the database where 15 model correlations have been tested. The best linear correlation has the AAE and ABE of 5.37 % and -1.00 % respectively. Based on the comparison with established correlations, the proposed linear correlation in this study shows the lowest error for both AAE and ABE indicating a reliable correlation has been obtained for estimating HHV of the raw and torrefied palm oil wastes.

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