Estimation of Moisture Content of Oil Palm Fronds through Correlation with Density for the Process of Gasification

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In the gasification process, one prominent factor that affects the quality of the resulting syngas is the moisture content of the biomass feedstock. Determining the moisture content of a feedstock is considered to be one of the challenges of the process. The information about moisture content of a feedstock is required to decide the need for further drying prior to the gasification process. In this study, a novel method was developed for the evaluation of the moisture content from density of oil palm fronds (OPF) in a sufficiently accurate manner for gasification process. A total of 147 samples from different sections of freshly pruned fronds were prepared. The density of each of the samples was determined from its weight and volume. A fine sand displacement method, using fine sand and a graduated cylinder, determined the volume of OPF. The moisture content of the OPF was determined from the weight difference of the samples before and after the drying process. The experiment implied a good correlation between moisture content and density of the biomass, in which the square of the correlation coefficient (R^2) value was found to be satisfactory.

Keywords: Moisture content; Density; Oil palm frond; Biomass; Drying

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INTRODUCTION

One of the prominent factors that affects the process of gasification is the moisture content of the feedstock. The problem is worse in coastal areas, where all the seasons have higher humidity, making it difficult to reduce the moisture content of the feedstock through natural drying processes. Moisture removal during gasification drains much of the deliverable energy in the gasification process (Dong *et al.* 2010). When the biomass is burned, part of the energy released is consumed in the conversion process of water into steam. As a result, if the biomass has a lower moisture content, then the energy available in it will generate more heat, which would enhance the efficiency of gasification (Rosillo-Calle *et al*. 2012; Kumar *et al*. 2014). Therefore, determining the feedstock moisture content and reducing it to the required level are considered as essential steps in the preparation of biomass feedstock for the gasification process.

In biomass, moisture can exist in two forms. The first form is as a free mass that resides outside the cell wall, whereas the second form is an inherent type, such that the water resides inside the cell walls (Simpson 1998; Basu 2010). The most common biomass moisture content evaluation technique, which is used for research and industrial application purpose, is the oven drying technique (Stahl *et al.* 2003). There are also various protocols and techniques that can be used to determine the moisture content of different types of biomass feedstock (Obernberger and Thek 2004; Singh 2004; Samuelsson *et al.* 2006a,b; Hartley and Wood 2008; Wu *et al.* 2011). However, these methods require either expensive equipment or longer time; hence, the methods are not viable for regular operations, such as in gasification and combustion processes, for the evaluation of the moisture content of biomass feedstock. Therefore, for such type of regular activities, a reliable and easy evaluation method is required.

In the past, researchers have attempted to develop methods to determine the moisture content of biomass, aiming to apply them for different purposes. A graphical relationship that indicates the equilibrium moisture content of wood in outdoor locations of the United States and in different parts of the world was developed as an aid to store kiln-dried lumber (Simpson 1998). In another report (Simpson 1993), an equation was developed for the determination of the density of wood from the moisture content for the purpose of estimating the shipping weight of wood using cubic samples.

The objective of this research was to develop a relationship between the moisture content and density of oil palm fronds (OPF) for the evaluation of the moisture content of OPF feedstock from its density prior to the gasification process. The moisture removal rate of OPF for a specified particle size using an oven at 105 °C was also investigated. Developing a correlation between moisture content and density of OPF cannot be achieved in the same way it has been done in the previous studies because of the difficulty to obtain regular shape samples by means of a cutting method, as OPF is fibrous in its nature. In addition, determination of volume by using a water displacement method is not favorable, as water would be absorbed by the OPF, and the resulting weight and density of OPF would be affected. Hence, a novel method was applied to estimate the volume of an irregular shape of OPF by using fine sand displacement method with a reasonable accuracy for the intended purpose. Finally, a correlation was developed that would enable prediction of the moisture content of OPF from its density for gasification process.

OPF is an abundant, but unutilized type of biomass waste in Malaysia. In 2009, the amount of OPF generated from pruning and re-plantation activities contributed to 46.7% of the total biomass waste, equivalent to 97 million tons per year. In terms of energy content, the contribution of OPF has been at about 405 x 10^6 GJ (Hassan *et al.* 1996; Shuit *et al.* 2009; CBBR 2010). The details of the characterization studies of OPF for use as a feedstock for the gasification process have been reported in previous papers (Sulaiman *et al.* 2010; Atnaw *et al.* 2011; Guangul *et al.* 2012a, 2014).

EXPERIMENTAL

Preparation of Samples

Freshly pruned oil palm fronds (OPF) were collected at Felcra classic oil palm plantation in Bota Kanan in the state of Perak, Malaysia. Fronds from different palm oil trees of the same species (*Elaeis guineensis*) were randomly collected, and samples were prepared on the same day of pruning. From previous works, it was ascertained that the moisture content of the steam of different trees varies with the variation of their stem height (Saatchi and Moghaddam 2000; Namoolnoy *et al.* 2010). Therefore, in this work, it was assumed that the same frond could have different moisture contents, and representative samples were prepared from different sections.

For the study, a frond with the leaflets removed was divided into three sections, *i.e.*, tip, middle, and hub, as shown in Fig. 1. The length of a frond can reach up to seven meters. At the hub end, the width and thickness may reach up to 200 and 100 mm, respectively, and both dimensions decrease toward the tip and become sharp at the end. In the study, the tip, middle, and hub parts of the frond were divided at 16/24, 5/24, and 3/24 length, respectively. Each section had an equal volume, with the assumption that the frond had a pyramidal shape with a rectangular base. The samples from each section were equal in number to obtain representative data for the whole fronds. The samples' weight and length were in the range of 15.23 to 19.62 g and 30 to 50 mm, respectively.

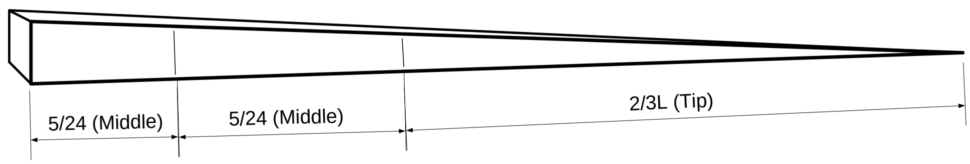

Fig. 1. Sections of a frond

Drying Process

In this study, two independent experiments were conducted. The first experiment was done to investigate the moisture removal rate and to determine the total time required for the removal of all residual moisture from OPF at a constant oven temperature. The second experiment was conducted to determine the correlation between moisture content and density of OPF.

Determination of moisture removal rate

Using a Carbolite 450 oven (UK), a continuous drying experiment was conducted to study the amount of moisture that could be removed from OPF samples in a set period of time at a constant temperature. A total of nine samples (three for each of the tip, middle, and hub sections) were prepared. The samples were placed in an oven at 105 °C for 24 h to ensure complete moisture removal and to obtain a constant weight, as suggested in the conventional drying method (Stahl *et al.* 2004). An Ohaus precision standard weighing balance (USA), which has an accuracy of 0.01 g, was used to measure the samples' weights. Initially, the weight of each sample (m_{Ii}) was measured before the drying process was started. During the first 15 h, the weight (m_{ti}) was measured at intervals of 30 min by taking them out of the oven and placing them back in the oven, as shown in Fig. 2. To ensure complete removal of moisture, the samples were kept in the oven for the remaining 9 h (from the 15th to the 24th hour) without withdrawal from the oven. At the 24th hour, the final weight (m_{3i}) measurement was taken for each sample by taking the sample out of the oven. From the results, graphs of the variation of sample weight and moisture with time were plotted and correlations were examined.

Determination of volume and density correlation

A total of 147 (49 for each section of the tips, middle, and hubs) samples were prepared to conduct an experiment for determination of moisture content and density relationship. An Ohaus precision standard weighing balance and Carbolite 450 furnace were used with the same conditions mentioned above. To identify the samples during the drying and weighing process, the tips were coded from T1 to T49, the middle from M1 to M49, and the hubs from B1 to B49, as shown in Fig. 3.

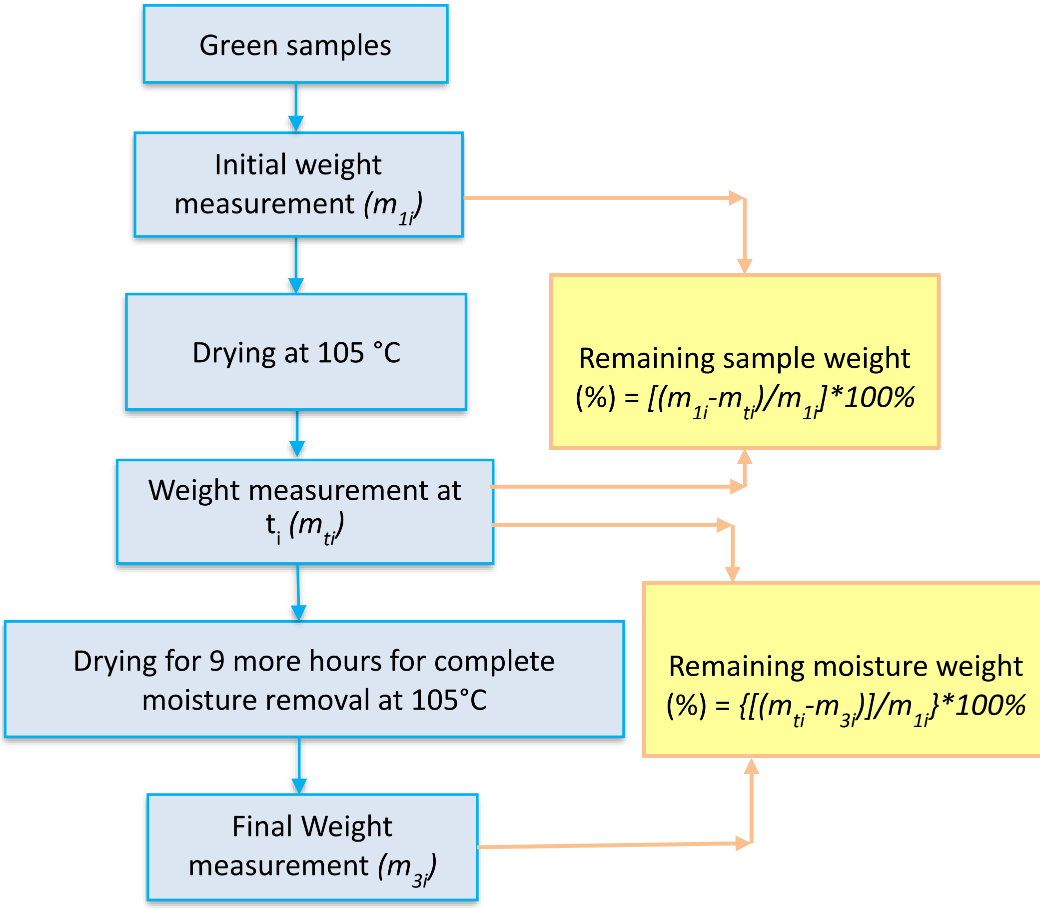

Fig. 2. Procedure for determination of the remaining weight percentage of the samples and moisture with time

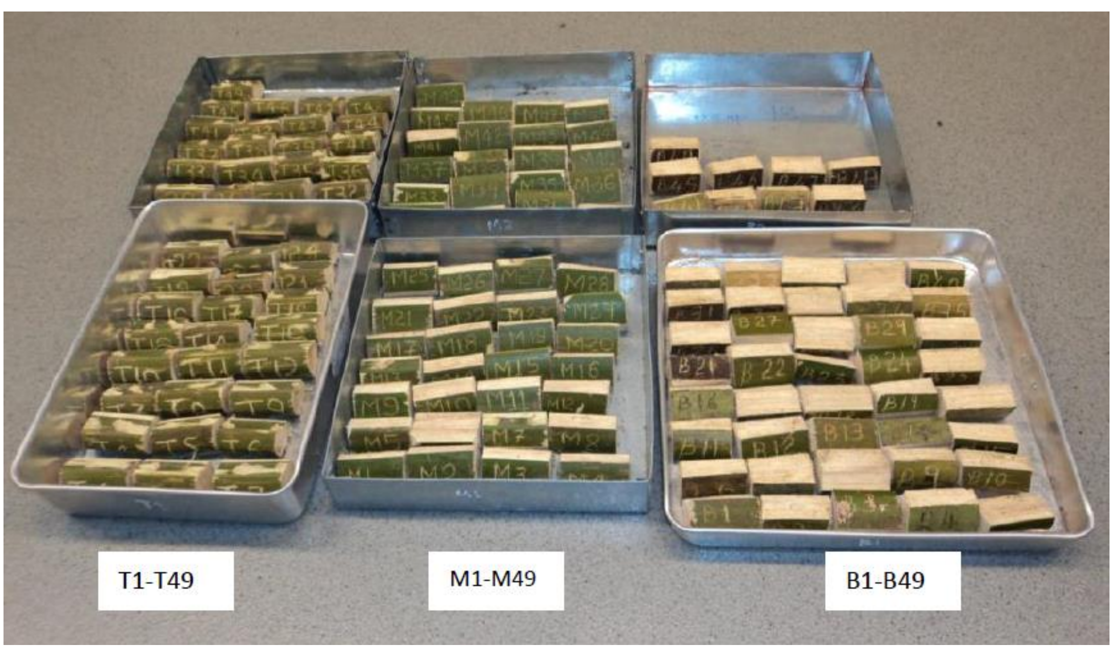

Fig. 3. Different sections of OPF

Determining the apparent volume of most biomass samples is not simple because of the difficulty in obtaining a regular shape by cutting or other methods. The water displacement method is also inappropriate, as the reading of the measurements would be incorrect because of the absorption of water by the pores of the biomass. Hence, in this study, a novel method was used to measure the volume of the samples with a reasonable accuracy for the intended purpose. A known amount of fine sand with particle sizes less than 0.18 mm and a graduated cylinder with 5-mL accuracy were used for the measurement. After the sample was placed in a graduated cylinder, 150 mL of sand was added to the cylinder, which was shaken to fill the void spaces. Then, the sample volume was calculated by subtracting 150 mL from the total volume reading.

Figure 4 shows the procedure for the determination of the relationship between density and moisture content of OPF. The weights of the samples were measured in two stages. The weights of three samples, T1, M1, and B1, were measured without drying and kept outside of the oven. The other 144 samples (T2-T49, M2-M49, and B2-B49) were put in the oven. The first weight measurements were taken by withdrawing three samples (one from each section) at a time, at 15-min intervals for 12 h to obtain different moisture contents in different samples. The volume of the samples was measured just after each time the first weight measurement was performed.

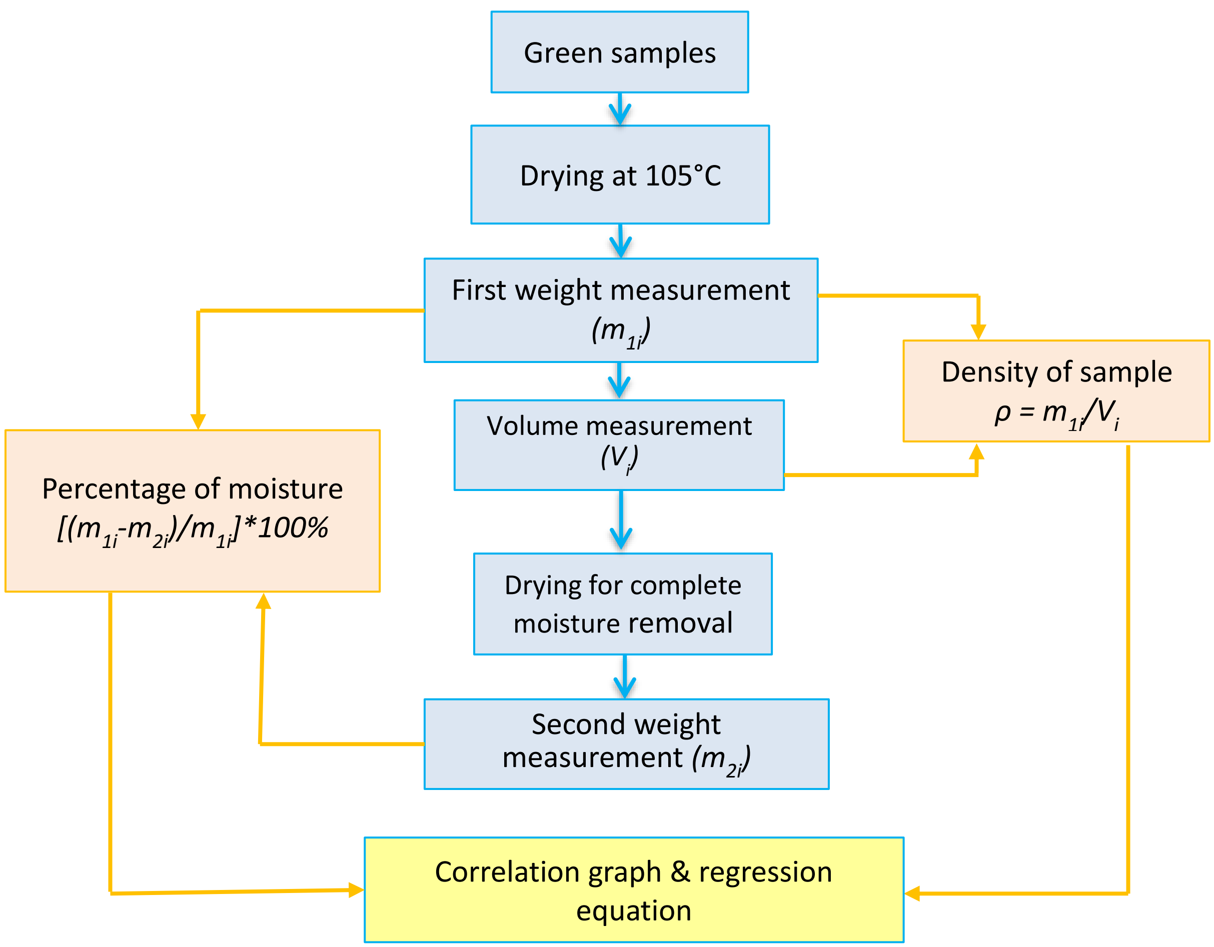

Fig. 4. Procedure for the determination of density and moisture content correlation

From the previous experiment, which was done for the determination of moisture removal rate, it was established that after 12 h of continuous drying at 105 °C, only a negligible amount of moisture in the range of 0.2% consistently remained in the samples. Hence, it was assumed that 12 h of drying was sufficient to draw a relationship between moisture content and density of the frond for the range of freshly pruned to fully dried samples. After completing the above process, all samples were taken back to the same oven and kept for 12 h at 105 °C to make sure all of the moisture was removed from all samples and, ultimately, weight measurements were carried out for a second time.

The density of the samples was calculated from the first weight measurement and succeeding volume measurement results, as shown in Fig. 4. The moisture weight percentages on a wet basis were determined by subtracting the second weight measurement results from the first weight measurement results. The first weight measurement results were the weights of partially dried samples, whereas, the last weight measurement results were the weights of completely dried samples. Hence, the correlation of density and moisture content for the tip, middle, hub, and the average of the three sections were obtained, and the relationship graphs were plotted from the above results.

RESULTS AND DISCUSSION

Amount of Removable Moisture in OPF

Figure 5(a) shows the variation of weight percentage of samples with time, and Fig. 5(b) shows the variation of the weight percentage of moisture with time for tip, middle, and hub sections under a continuous drying process at 105 °C. The maximum calculated standard deviations for the weight percentage of the samples from the mean value for tips, middle, and hubs were 2.2%, 2.2%, and 2.4%, respectively. Also shown in the figures are the average weight percentages of the samples and moisture removed from the samples for all sections, with a maximum standard deviation of 3.8% from the mean value. As shown in Fig. 5(a), the curve corresponding to the hub section is steeper than that of the middle and tip sections. In addition, the total amount of moisture removed from the hub section was higher than that from the middle and tip sections. This suggests that the hub section had more initial moisture content than the middle and tip sections. The same held true also in the comparison of the graphs for the middle and tip sections. This therefore establishes that the initial moisture content of the hub section was higher than the middle section, and the middle section was higher than the tip section. It can be inferred from Fig. 5(a) that the completely dried sample weight of the hub section was only 28.1%, while the middle and the tip sections were 30.4% and 31.4%, respectively, of the original weights.

The tolerable amount of moisture in a downdraft gasifier is below 20% (Roos 2008; Gautam 2010; Guangul 2012b). In the current study, OPF required approximately 3 h of continuous drying under the stated conditions to achieve this level of average moisture content on a wet basis. The average moisture content of the samples dropped to 16.5% in 4 h, and after 5.5 hours, the moisture had dropped below 10% on a wet basis. It is also interesting to note that after the first 12 h of drying, the amount of weight reduction for the remaining 12 h was only 0.2% for the tip and middle sections and 0.4% for the hub section. The reduction of these weight percentages was thought to be not only a consequence of moisture removal, but falling of flakes was also observed during handling of samples in the process of weight measurement. Therefore, it can be concluded that the amount of moisture remaining in the samples after 12 h of drying in the above condition is minimal and the density *versus* moisture content relationship investigation can cover the range of green to completely dried samples.

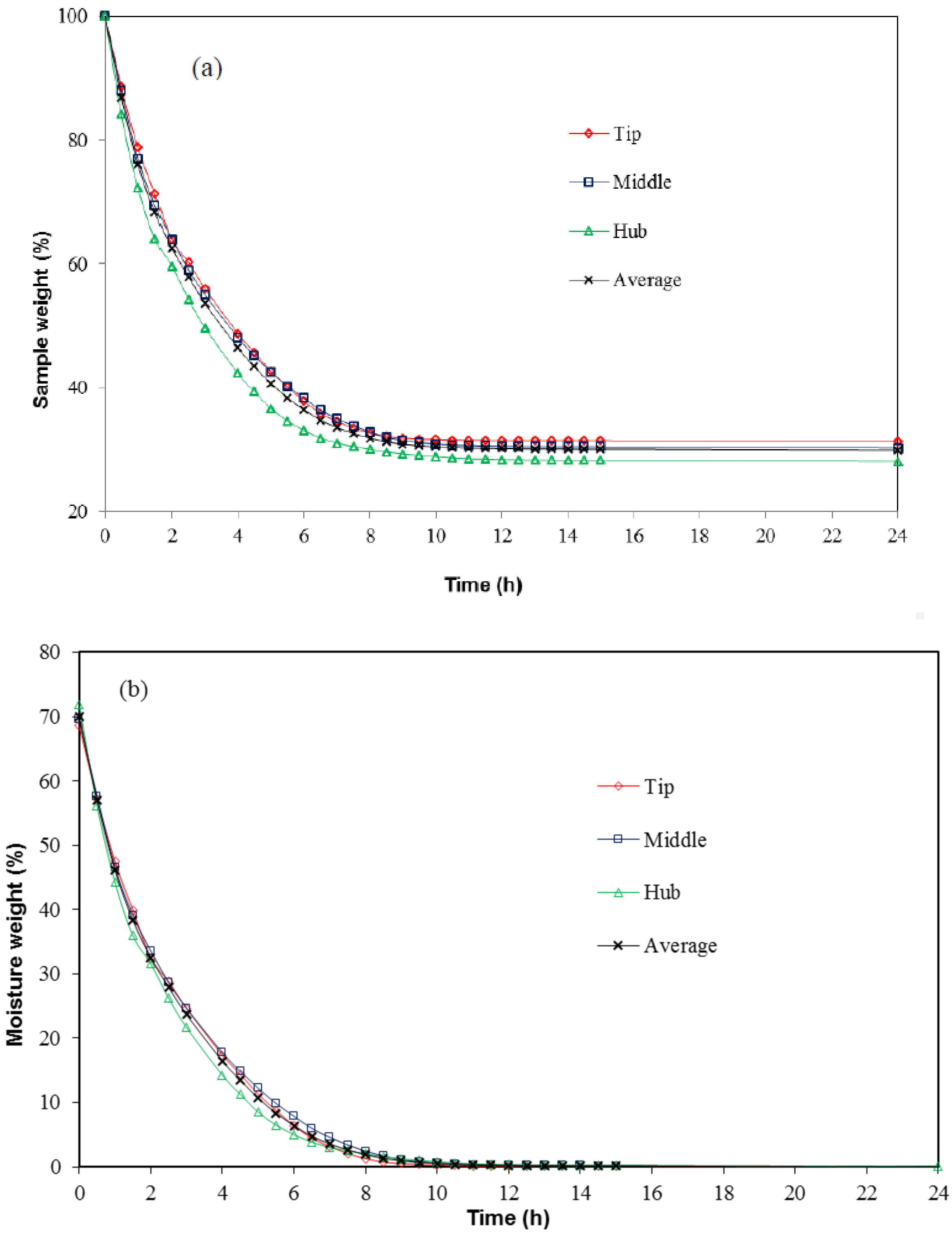

Fig. 5. Variation of (a) sample weight and (b) moisture weight with time

Moisture Content-Density Correlation

The density of biomass is dependent on many factors, such as latewood percentage, wall thickness, cell size, and moisture content (Simpson 1993; Espinoza 2003; Rhén *et al.* 2005; Serrano *et al.* 2011).

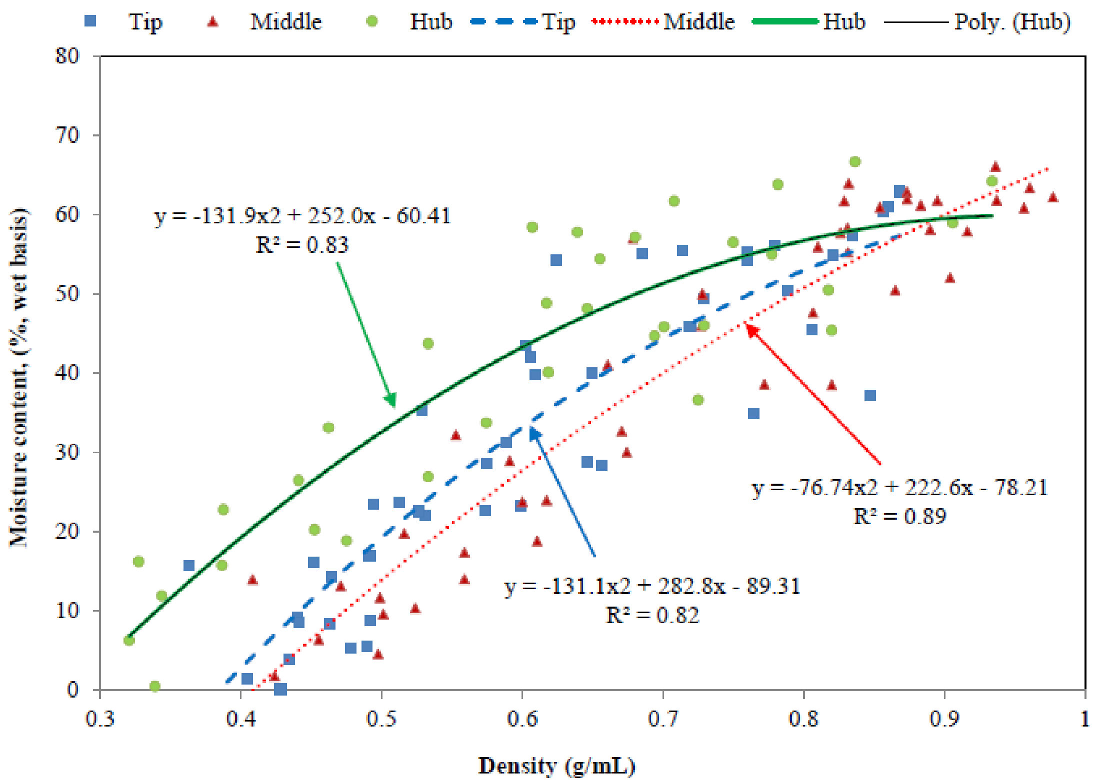

Fig. 6. Variation in wet basis of moisture content with density of different sections of oil palm frond

The graphs in Fig. 6 were plotted considering the variation of moisture content with density for the tip, middle, and hub sections separately. For the regression analysis, an Excel spreadsheet program was used and a second-order polynomial function model fits best, with coefficient of determination (R^2) values of 0.82, 0.89, and 0.83 for tip, middle, and hub sections, respectively. As the R^2 values indicate, moisture content and density had a positive and strong correlation. However, on the graph, some points appear far from the trend line. This may have happened for many reasons. The first cause may have been human errors as the volume and/or weight measurements were taken. Particularly, as the volume measurement was done using fine sand in a graduated cylinder, there might have been human errors involved in keeping the surface level horizontal, even though caution was taken to minimize the errors. Also, there may have been the variation among the samples, as they were prepared from the same section, but at different spots of a frond as well as from the same section of different fronds, as there are other inherent factors that may affect density besides moisture content (Taylor 2006).

From the graphs, it can be observed that a decrease in moisture content led to a decrease in density. For the same density value, the hub section had more moisture content than the other two sections and the middle section had the least moisture content. At the lowest moisture content, the hub section density was lower than the other sections; when the moisture content increased and reached the highest point, the density difference exhibited from section to section of the frond became minimal. Initially, when the moisture content was higher and the vessels of the biomass tissue were filled with water, the effect of other factors on density variation, like volume ratio of vessels to fibers and fiber wall thickness, were less pronounced (Parham and Gray 1984). When the moisture is removed, the density difference will depend more on the other factors, which may vary from section to section. Generally, the shrinkage amount of biomass depends on the amount of water removed, the orientation of micro fibrils in the cell wall, and the relative density of the piece (Jozsa *et al.* 1998). In simple terms, density is weight per unit volume. As the samples dry more, weight and volume will be reduced more, but the weight reduction is faster than the volume reduction; hence, the measured density will decrease when the moisture content decreases. In general, the experimental results showed that density increases with an increase in moisture content. Furthermore, for the same moisture content, the middle section of the fronds was found to be denser than the other sections, with the hub section found to have the lowest density value.

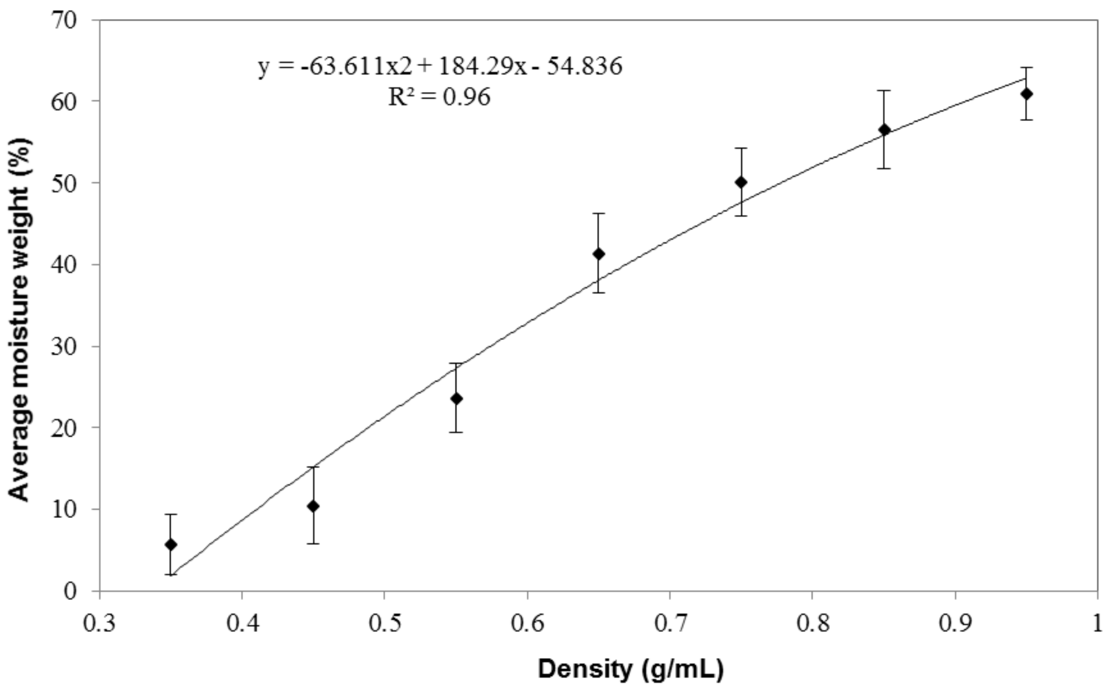

Fig. 7. Variation in wet basis of moisture content with density and standard errors

Because the tip, middle, and hub sections of OPF are used as a feedstock together after chopping, a graph that represents the average moisture content of OPF feedstock is required for prediction of the moisture content from representative samples during the gasification process. Shown in Fig. 7 is the variation of moisture content of OPF with the standard errors of the mean values. This result was obtained by combining the data points for all the samples of the three sections of fronds in intervals of 0.1 ranging from 0.3 up to 1. The calculated maximum value of standard errors of the mean was 4.9% at a density value of 0.65 g/mL. In the regression analysis with a second-order polynomial function, a coefficient of determination (R^2) of 0.96 was obtained for the average values of variation of moisture content with density.

As shown in Fig. 7, at the lower and higher moisture content the smooth curve tended to be steeper in comparison to the real data. At higher moisture content, particularly the freshly pruned fronds, *i.e.*, before drying, the moisture content of different parts of the frond reaches up to 70%. Hence, the variation on density of the tip middle and hub parts is minimal, since the density value would strongly depend on the moisture contained in the frond than other lignocellulosic components as shown in Fig. 6. Consequently the prediction at higher moisture contain is more consistent and closer to the real value. At the lower moisture content, as shown in Fig. 6, the variation between different parts of the frond is higher compared to that of higher moisture content. The main reason is the influence of moisture on density would be minimal, and the difference is mainly dependent on lignocellulosic components of the frond. At the lower moisture content, however, the prediction is steeper than what is indicated by the real data, such as the higher moisture content, as shown in Fig. 7. A possible reason could be offsetting of extreme values of both sides during averaging.

CONCLUSIONS

1. From the current study, the fresh oil palm fronds (OPF) samples were found to have initial moisture content as high as 70% on wet basis. It was also ascertained that oven drying at a temperature of 105 °C for 3 h is sufficient for a particle weight of 20 g to get a workable feedstock with moisture content below 20% for gasification use in downdraft gasifier.
2. In addition, it was established that for the same particle weight 12 h of drying at 105 °C oven temperature is sufficient to obtain completely dried OPF feedstock from freshly pruned OPF. This result of 12 h optimal drying time was used as benchmark for the investigation of density and moisture content correlation.
3. From the correlation study, a sufficiently accurate result was obtained for quick prediction of the moisture content of OPF feedstock from its density for the purpose of gasification process.
4. From the regression analysis of the variation of moisture content with density of fronds, a second order polynomial function with 0.96 value of coefficient of determination (R^2) was obtained, which indicates a good correlation of the two parameters.

ACKNOWLEDGMENTS

The authors would like to acknowledge Universiti Teknologi PETRONAS for providing the funds for this research work.

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Article submitted: June 11, 2016; Peer review completed: August 7, 2016; Revised version received and accepted: August 26, 2016; Published: September 7, 2016.
DOI: 10.15376/biores.11.4.8941-8952