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Investigation of the relationship between moisture content and density of selected Malaysian biomass

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ABSTRACT

Suspended moisture in raw biomass materials is undesired in biomass fuel applications. In commercial and industrial practices, the moisture content in biomass fuel is normally in between 10-20% by weight in order to maximize the heating value of the fuel. Determining the moisture content in biomass materials using the conventional oven-drying method is time consuming. This paper studied the linear relationship between the density and moisture content in several Malaysian lignocellulosic biomass residues from palm oil (oil palm frond, oil palm trunk, oil palm leaf, empty fruit bunch, palm mesocarp fiber and palm kernel shell), rice (rice husk), coconut (coconut frond and shell) and sugar (sugarcane bagasse) industries and their potential function as a tool for moisture determination with reference to their density. The biomass moisture content and density were determined through the oven drying method at 105°C and constant volume weighing at every 1-hour drying interval. All samples showed a linear relationship between moisture content and density, and a linear model for each biomass was constructed. The linear models were cross-validated using a set of measured observations to determine the prediction reliability and accuracy at 95% confidence interval. The cross validation regressions revealed the R^2 and adjusted R^2 values of above 0.9, while the standard error of regressions was found to be less than 3.1 wt. % of moisture content for all linear models except for that of rice husk, indicating that the linear models are statistically reliable and accurate for moisture content determination using density. The average time of moisture determination using the density-moisture content models was found to be only between 45-60 minutes compared to the conventional drying method that took 24 hours to complete.

Keywords: *biomass, solid fuel, lignocellulosic, renewable & sustainable energy*

INTRODUCTION

In the advent of renewable and alternative energy resources and technology implementations, biomass has been widely utilized as fuel from the consumer to industrial scale to generate heat and electrical power [1-3]. Biomass fuel does not contribute to the global carbon footprint and has proven to be a beneficial fuel material in direct and indirect combustion applications [4-9]. In Malaysia, biomass residues from the palm oil industry are used as boiler materials at palm oil mills for steam generation, other than to produce potash ash for fertilizer production [10] Palm oil residues, particularly empty

fruit bunch (EFB) and palm kernel shell (PKS), are also used to produce second generation liquid fuel [11, 12]. Several more studies showed the potentials of oil palm frond (OPF) as a solid gasification fuel to generate heat and electricity [13-16]. However, most raw biomass materials need to go through a pre-combustion processing to convert them accordingly into fuel material [1, 2]. The processing includes sizing, densification and drying. While some biomass materials can be utilized directly without undergoing sizing and densification, most of them need to undergo the drying process to remove excess moisture. Normally, raw biomass, especially those of the native to tropical climate, may contain up to 60% moisture in the natural and processed states when collected. Moisture content in biomass leads to its natural decomposition, dropping combustion performance due to inefficient firing, and may cause excess formations of liquid products such as tar and condensates that will further affect the quality of the combustion products [17-19]. Furthermore, moisture content lowers the calorific value of fuel due to the irrecoverable heat required to convert water to steam during combustion. In commercial and industrial combustion practices, biomass fuels need to contain 20% or less moisture content to avoid operational difficulties and performance issues [17]. Raw biomass is usually dried using natural sun-drying method or artificial method by means of a convection oven or waste heat from boilers and furnaces. For an extended storage time, the moisture content in biomass is commonly reduced to below 5%. However, biomass may still gain moisture while in storage. Dry biomass exhibits a hygroscopic behavior where its moisture content will vary with its ambient humidity. Dry, fibrous biomass tissue will absorb and release a small amount of moisture to and from its environment according to the ambient humidity level until it reaches the equilibrium moisture content where no gain and loss in moisture content is achieved, and this is generally a slow process. The hygroscopicity of biomass was investigated by Guangul et al. [18] on oil palm frond, where up to 12% gain and loss in moisture content was observed in dry OPF. The hygroscopic properties of biomass are important in designing a storage space free from humidity to curb the absorption of suspended moisture in the air that will lead to biomass decomposition and reduced storage life [13]. Due to the hygroscopicity of dried biomass that influences its equilibrium moisture content while in storage and will ultimately affect its combustion performances, the biomass is usually subjected to a moisture content test to determine its moisture content.

To precisely measure the amount of remaining moisture in wet and dry biomass, the oven-drying method is conventionally used, where biomass sample is exposed to a temperature of 105°C for 24 hours, from which the change between the initial and final masses represents the sample's moisture content [18-20]. The process is deemed as time consuming and may cause delay to the biomass utilization. Therefore, a quicker and reliable method to determine the moisture content in biomass is much required. Previously, the relationship between the two parameters in OPF has been noticed to be directly proportionate; density reduces with the dropping moisture content in a linear trend [18-20]. This is due to the reduction in mass from loss of moisture in the sample during drying that consequently affects its density. The linear relationship between density and moisture content of a specific biomass could provide an interesting use: it could be a helpful and reliable tool to accurately determine the moisture content in any given biomass sample of the same type in a much quicker way compared to the oven drying method. A more detailed study conducted by Sulaiman et al. concluded the potential usage of particle density to determine the moisture content in OPF [19]. As of present, very few existing studies have reported on the density-moisture relationship in

biomass, and the existing ones discussed only generally on timber and several oil palm residues [18-23].

The biomass materials utilized in this study are native to Malaysian industries and exist nationwide in a large quantity [24]. The biomasses are composed of lignocellulosic materials with woody to fibrous physical properties, exhibiting the wide morphological diversity of Malaysian biomasses. Two types of biomass based on origins were used in this study: plantation-based and mill-based. Mill-based biomass is normally the by-product of crop processing such as rice husk (RH) from rice production, coconut shell (CS) from coconut flesh production and similarly, empty fruit bunch (EFB), palm kernel shell (PKS) and palm mesocarp fiber (PMF) from the extraction of raw palm oil, sugarcane bagasse (SB) from sugar pressing, and refuse wood (WD) from log processing. Mill-based biomass is easier to collect due to established infrastructures and facilities for temporary holding, gathering and transportation. Plantation-based biomass is produced during the harvesting period such as oil palm frond (OPF), oil palm leaflet (OPL), coconut frond (CF) or from replanting such as oil palm trunk (OPT). Plantation-based biomass is sometimes difficult to reach due to varying terrains and limited access. The palm oil industry is the biggest contributor of biomass wastes in the country, producing more than 70 million dry tons in 2009 [7]. The timber industry is the second biggest, followed by rice, coconut and sugar industries in that order. The total estimated amount of available biomass in Malaysia in the year 2009 was nearly 80 million dry tons [7]. A more accurate and recent estimate done on the availability of unused Malaysian biomass is shown in Table 1. This estimate was done after taking account of the actual production amount based on the residue to product ratio and the accessibility and recoverability factors, giving off the more precise and realistic estimate of the unused amount of biomass residues in Malaysia in 2015. In total, around 23.1 million tons of unused dry biomass residues were generated, with a total potential energy of 408.8 PJ.

Table 1. Selected types of Malaysian biomass and their productions in 2015.

Residue type	Representative calorific value , MJ/kg	Annual availability, ton db.	Total potential energy, PJ
OPF	17.59	11,370,989	200.02
OPT	17.31	110,970	1.92
EFB	18.44	2,186,729	40.32
PMF	17.81	3,110,014	55.39
PKS	18.64	1,943,759	36.23
RH	16.87	214,132	3.61
CF	15.33	10,791	0.17
CS	20.64	60,697	1.25
SB	17.33	420	0.01
WD	18.48	4093380	69.88
Grand Total		**23,101,881**	**408.8**

This study aimed to investigate the relationships between the density and the moisture content of selected Malaysian biomass residues, and to develop biomass-specific, reliable and accurate density-moisture content linear models to function as a tool for a quick moisture content determination in biomass residues. It was presumed that the same relationship is demonstrated by other Malaysian lignocellulosic biomass materials. This tool is anticipated to provide biomass users to determine the moisture content in their

samples without undergoing the time-consuming oven drying test. The study also focused on the hygroscopicity and the equilibrium moisture content in the tested biomass residues while stored in ambient conditions for user reference in storing dried biomass.

MATERIALS AND METHODS

Biomass Pre-processing

The pre-processing stages of the biomass residues are shown in Figure 1. The selected biomass samples were first collected from the respective mills and plantations in their natural or processed state. All oil palm biomass residues were collected from the plantation and mill operated by FELCRA Nasaruddin, Bota, Perak. The CF, CS and SB were collected from a private-owned plantation, a sundry market and a sugarcane juice seller respectively, all located near the university. The WD was collected at a sawmill near Simpang Pulai, Perak. Large residues such as OPT, OPF, CF and EFB were chopped to block sizes of 50-100 mm in apparent dimensions. The biomasses were ground to granule size using a plastic granulator to a particle size range of ≤ 5 mm. The granules were then sieved using 5-mm and 3-mm sieve nets to separate coarser granules and dust, and to collect particles with the apparent dimension range of 3-5 mm. The dimension range was used due to the limitations of the oven size and precision balance. The processing stages were completed within 12 hours upon receiving the biomass residues at the laboratory to minimize the effects of natural decomposition and to increase measurement accuracy.

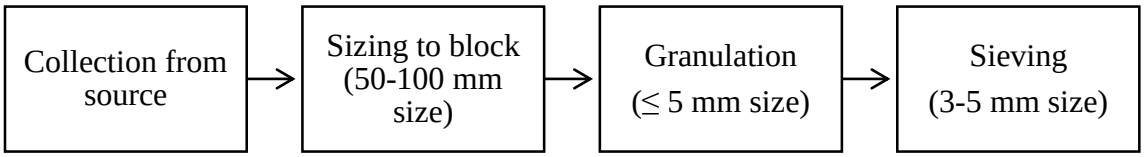

Figure 1. Pre-processing stages of biomass residues

Determination of Moisture Contents, Hygroscopicity, Density and Density-Moisture Content Relationship

The flowchart of the tests and analyses is shown in Figure 2. The processed samples were filled up in cylindrical metal cans with identical volume and were shaken thoroughly to achieve a uniform particle distribution. A total of 33 samples (3 samples for each biomass) were prepared. The initial mass of each sample was measured using a Mettler-Toledo ME3200/0.01g precision balance scale. Biomass densities were calculated using mass and volume relation based on ASTM D1895-96 and ASTM E-873-82. The volume of each container was measured using a Vernier caliper with readings at 0.01 mm precision. The determination of biomass moisture content method used was based on ASTM D4442-15. Each sample was placed in a Carbolite 450 convection oven at 105±0.5°C and left to dry for 24 hours until the change in mass was found to be ±0.1% for three consequent readings, with the assumption that nearly 0% moisture content had been achieved. The change in mass of each can was measured at an hourly interval for the first 10 hours of drying to determine the loss of moisture and its effects to density. The samples were then placed in an open, shaded space with a temperature range of 23-26°C and humidity level of 70-80% for 48 hours to replicate an indoor storage condition before their final masses were measured for the determination of equilibrium moisture content (EMC) and hygroscopicity. All measurements were made three times for each reading and the

experiments were repeated three times to ensure data consistency and experiment repeatability. The density-moisture content relation of the samples was tested using regression analysis for the R^2, adjusted R^2 and SER values. The linear regression trend was then plotted for each sample and the linear trend equation was obtained.

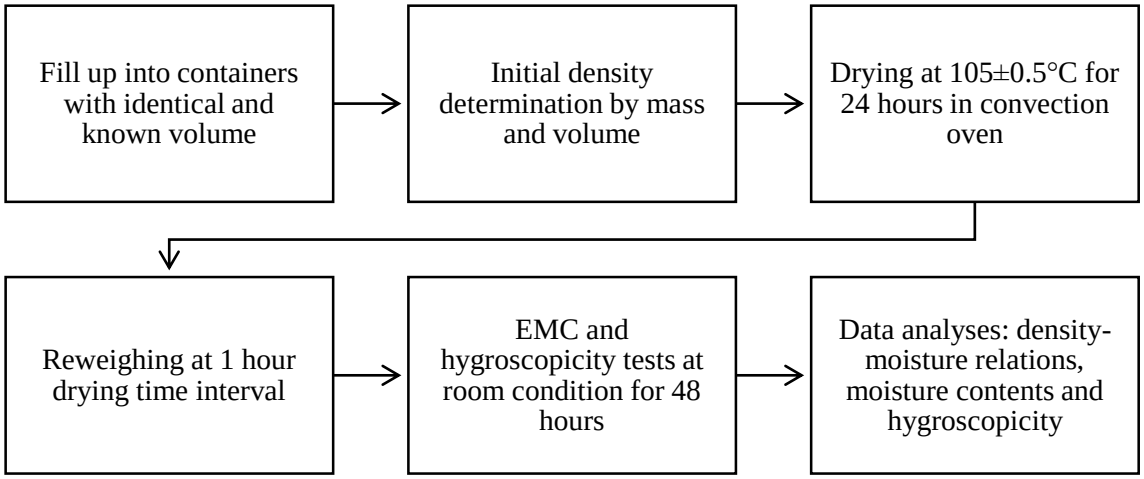

Figure 2. Determination of moisture contents, hygroscopicity, density and density-moisture content relation.

Model Validation

The density-moisture content plot constructed for each biomass residue based on the readings obtained during drying and weighing tests was evaluated using the fitting performance criteria for model validation and determination of accuracy. The plots were later validated against a separated set of measured data for the evaluations on prediction reliability and accuracy, as shown in Figure 3. The performance criteria utilized for the models were the correlation coefficient (R^2), adjusted correlation coefficient (Adj. R^2), standard error of regression (SER), Average Absolute Error (AAE) and Average Bias Error (ABE), following the work of Elneel et al. in evaluating correlations for OPF gasification [25]. Correlation coefficient is widely used for statistical and regression analyses with the objective to determine the accuracy of mathematical models, where high R^2 value indicates better model estimation capability, with R^2=1.0 portraying a perfect model. While R^2 assumes that every single variable explains the variation in the dependent variable, the adjusted R^2 reveals the percentage of variation explained by only the independent variable that affects the dependent variable. Adjusted R^2 is useful in analysing multivariable data, while for the single independent variable model, R^2 and adjusted R^2 are interchangeable. Standard error of the regression (SER) is the precision which the regression coefficient is measured, where it explains the distance where the observed values fall from the regression line. SER values of closer to 0 are better, indicating that the observations are closer to the regression line and therefore improving the regression fit. All regressions were made at 95% confidence interval. The AAE and ABE describe the accuracy and bias of the correlation; the lower the AAE value, the higher the accuracy of the model, whereby a positive value of ABE indicates the overall over-estimation and a negative value of ABE indicates the overall under-estimation of the model (the smaller the absolute value of ABE, the smaller the correlation bias, with ABE=0 portraying a perfectly unbiased model). In this study, regression statistics were computer generated while AAE and ABE were manually calculated using the following equations:

$$\text{AAE} = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{BD_C - BD_M}{BD_M}\right| \times 100\% \quad (1)$$

$$\text{ABE} = \frac{1}{n}\sum_{i=1}^{n}\frac{BD_C - BD_M}{BD_M} \times 100\% \quad (2)$$

where subscribes M and C denote the measured and calculated values for density (BD) respectively, while the number of samples in the population is denoted by n. Each model was cross-validated using random sampling of the respective residues at varied moisture contents. A total of 30 samples were used for the cross-validation of each model. The cross validation results were subjected for a regression analysis to determine the reliability and the accuracy of the model prediction ability at 95% confidence interval. Only cross-validated models with high reliability and accuracy will be accepted as tools to quickly determine the moisture content in specific biomasses that each of the model represents, using only the density of the biomasses.

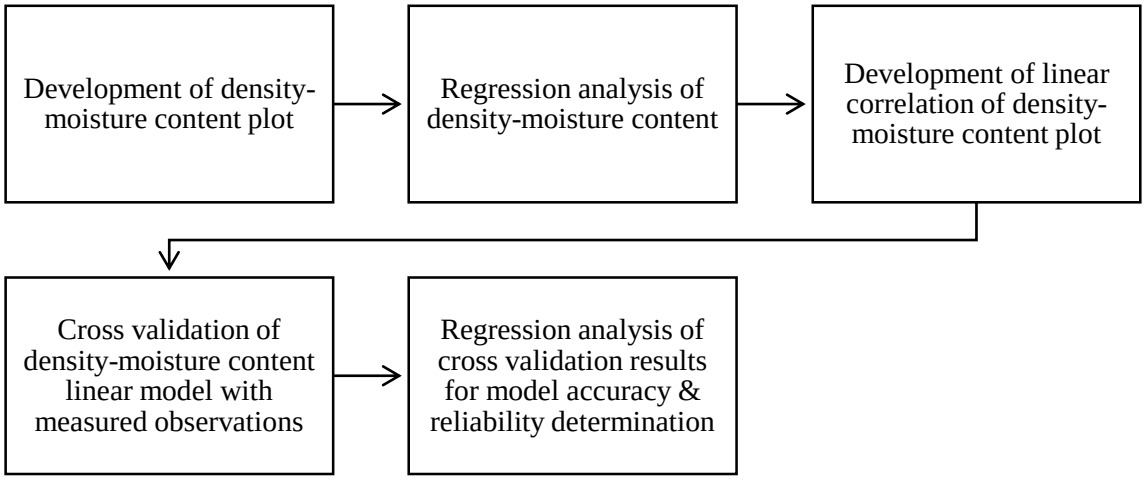

Figure 3. Process flow of density-moisture content linear model development and analysis and the validation of the linear model.

RESULTS AND DISCUSSION

Moisture Content and Hygroscopicity

The as-received and equilibrium moisture contents of the selected Malaysian biomasses used in this study and their hygroscopicity are shown in Table 2 and depicted in Figure 4. RH was found to be relatively the driest sample while OPF was the wettest on the as-received base. This was mainly due to the processing and storage variants for each of the residues and also the structure of the fibrous tissues in the samples, where herbaceous biomass with a high pith fiber content like sugarcane normally contains high moisture [26]. Field-based residues from the oil palm industries like OPF, OPT and OPL are considered green biomasses that undergo no mill processing and are freshly produced during field maintenance and/or replanting practice [13, 14]. OPT and OPF contain up to 60% moisture during production and the natural drying process upon production takes a considerably long time due to their bulkiness. Although OPL is a part of OPF, it contains

fairly less moisture due to its thin form with a large surface area that promotes faster release of water to the environment. EFB, PKS and PMF are by-products of the oil palm extraction process and are required to undergo boiling and steaming to break down their fibrous tissue structures for process convenience. This results in a significant increment of water content in the residues. When removed from the processing area, the wet residues are collected separately in a pile. Based on the observations made during sample collections for this study, EFB was seen stored in an open yard while PKS and PMF were stored within the mill area. The thickness of the pile and the fibrous nature of the residues held the water within, resulting in a slow drying process as reflected in their moisture contents. EFB was relatively drier than PKS and PMF since it was directly exposed to the sun while in storage at the mill's open yard; the advantage of warmer storage temperature and moving draft resulted in a relatively quicker drying. CS, CF and WD had moderate moisture contents of within 10-25%, and this was due to their semi-dry state when collected. The water content in CS mainly comes from the coconut juice caught in the CS fiber during the breaking of the coconut and from the leftover coconut flesh still attached to CS after flesh extraction. As for SB, its water content is mainly the remaining juice that is still caught within its crushed fiber even after the secondary pressing stage. Unlike OPF that is pruned off the oil palm tree, CF is produced simply by letting it dry in the air and naturally falling off the coconut tree, subsequently removing a substantial amount of water content in the process. WD exists in the forms of chip, shaving, block, offcut and sawdust that are produced from logs that have been dried in the open prior to processing, and the residues undergo further drying in the collection pile [27]. RH is typically the driest due to the processing requirement of rice extraction, where the grains are first aired to dry, resulting in a very low moisture content in RH.

Table 2. Moisture content and hygroscopicity of selected Malaysian biomass.

Biomass Type	Moisture Content, %		Hygroscopicity, %
	As Received	Equilibrium	
OPF	66.61	14.14	±5.03
OPT	60.13	11.45	±5.54
OPL	13.70	11.25	±0.02
EFB	23.15	13.42	±0.02
PKS	47.98	6.93	±1.11
PMF	34.39	9.76	±0.84
CS	23.27	6.73	±3.69
CF	14.71	19.27	±1.16
WD	12.97	10.46	±1.99
RH	6.19	11.55	±5.48
SB	27.67	11.37	±2.40

The EMC of all biomass samples were within 9-14%, except for PKS and CS which were lower (around 6-7%) and CF being the highest at 19% due to the hygroscopic nature of the residues. The phenomenon where one material is more hygroscopic than the other is perceived as still a mystery, but generally, it is believed to happen due to the crystalline structures within and the electrostatic environment of the solid as described by VanLang [28]. CF exhibited a rather significant increment in moisture similar with RH, and can be attributed to the stock fibrous tissue structure that actively absorbs more moisture from the environment as a function of relative humidity. This is also highly

believed to occur due to the existence of certain crystalline minerals, primarily salts, trapped in the fibrous tissues of the residues that cause elevated hygroscopicity. High porosity of the residues may as well play a significant role through capillary condensation action, as often demonstrated by zeolites, where water is continuously absorbed by the compound from the environment like a sponge absorbing water, much ascribed by the oxygen-hydrogen bonding activities on an atomic level [29].

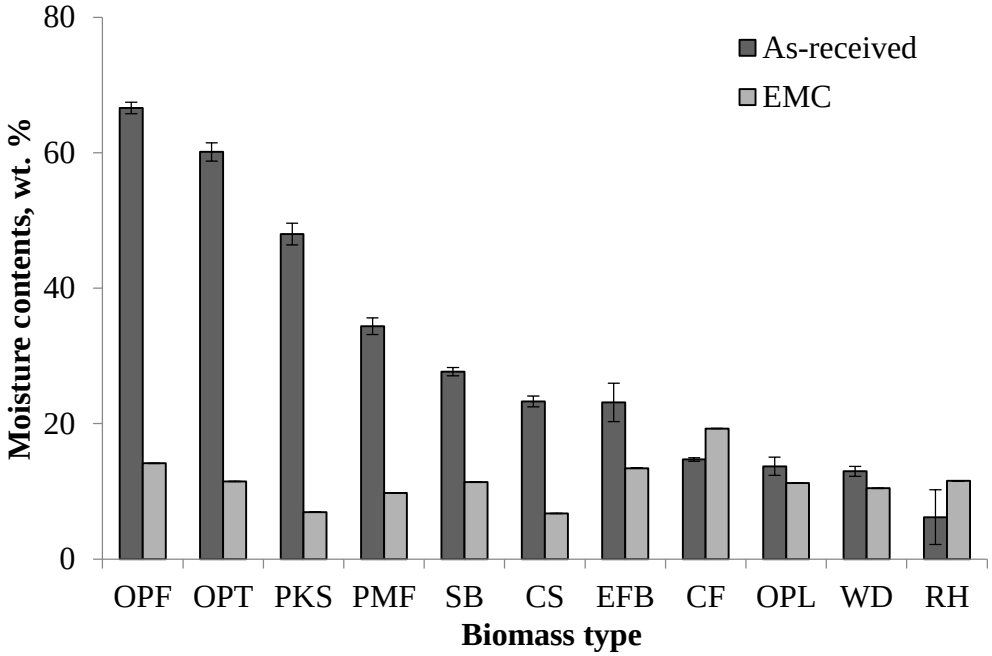

Figure 4. As-received and equilibrium moisture contents of selected Malaysian biomass materials.

This means that a wet biomass material with a moisture content above that of EMC will release its moisture to the environment, while a dry biomass material with a moisture content below that of EMC will gain moisture from the environment until the EMC is met. The biomass EMC indicates the minimum achievable moisture content from natural drying, and is ideal for the unconditioned storage environment of biomass. Hence, drying the biomass until its moisture content is lower than EMC has no advantage if it is intended to be stored for more than 48 hours. The hygroscopicity of the biomass samples showed a value range of 0-5.5%. The hygroscopicity of biomass samples was more aggressive at the beginning of measurement, but became nearly dormant as the moisture content level moved near to EMC. This was due to the reduced hygroscopicity action as the amount of water that had been absorbed/released from the residues was closing to the limit dictated by the relative humidity. Since hygroscopicity is directly related to the fluctuations in ambient humidity and temperature, biomass storage has to be conditioned to minimize the fluctuations and altogether reduce the hygroscopic effect for better preservation and extended storage life. This can be done by limiting the exposure of the storage area to high humidity, by employing moisture absorbance material in the storage and also by introducing draft into the storage area using ventilation fans.

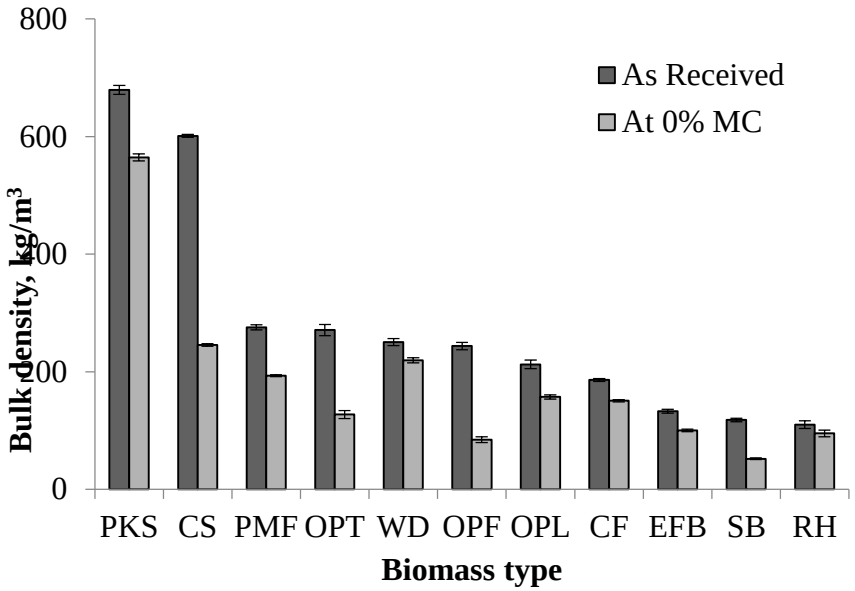

Figure 5. As-received and fully-dried densities of selected Malaysian biomass materials.

Table 3. The densities of selected Malaysian biomass.

Biomass Type	Density, kg/m^3		Density Loss, %
	As Received	At 0% MC	
OPF	243.68	84.40	-65.34±2.49
OPT	270.94	127.16	-53.01±3.56
OPL	212.49	157.13	-25.96±3.68
EFB	133.11	100.36	-24.56±2.87
PKS	679.23	564.50	-16.88±1.51
PMF	275.40	193.17	-29.84±1.44
CS	601.11	245.47	-59.09±4.87
CF	185.97	150.80	-18.90±1.74
WD	250.49	219.48	-12.33±3.22
RH	110.01	95.20	-13.17±8.43
SB	117.98	51.81	-56.06±1.83

Density

The shaken densities of the selected Malaysian biomass samples in the as-received and fully dried bases are shown in Table 3 and depicted in Figure 5. OPF, OPT, PMF and CS suffered density losses of above 50%, mainly contributed to the liberation of trapped moisture during drying. PKS and CS, due to their tough, near wood-like morphology, had the highest densities relative to other samples which were mostly made up of loose, non-woody fibers. Generally, woody plants have higher densities due to more packed tissue structures compared to softwood and herbaceous biomass materials [1, 2, 30]. The densities of the rest of the dried samples were found to be lower than that of WD, with SB being the lowest. Sugarcane is a perennial true grass by species and the stalk typically contains only 9-17% fiber, whereas most of the stalk is made of 12-20% soluble and insoluble sugar and 63-73% water [31]. The fiber content is primarily made of parenchyma – a common pith fiber of non-woody plants – while the rest is comprised of sclerenchyma that makes the rind and stem [31, 32]. When water is removed from the

stalk during the pressing process, voids are created in its tissue structures, causing the produced SB to be highly porous. This consequently makes SB to have a highly inhomogeneous and lightweight, fluffy and spongy texture when dried, and is reflected in its density.

Density-moisture content relations

The density-moisture content relations of the selected Malaysian biomass samples are shown in Figure 6, while the generated linear model correlation for each sample is shown in Table 4 with the respective R^2 and adjusted R^2 values. The linear relations were constructed using the density measurements at varying moisture contents obtained during drying.

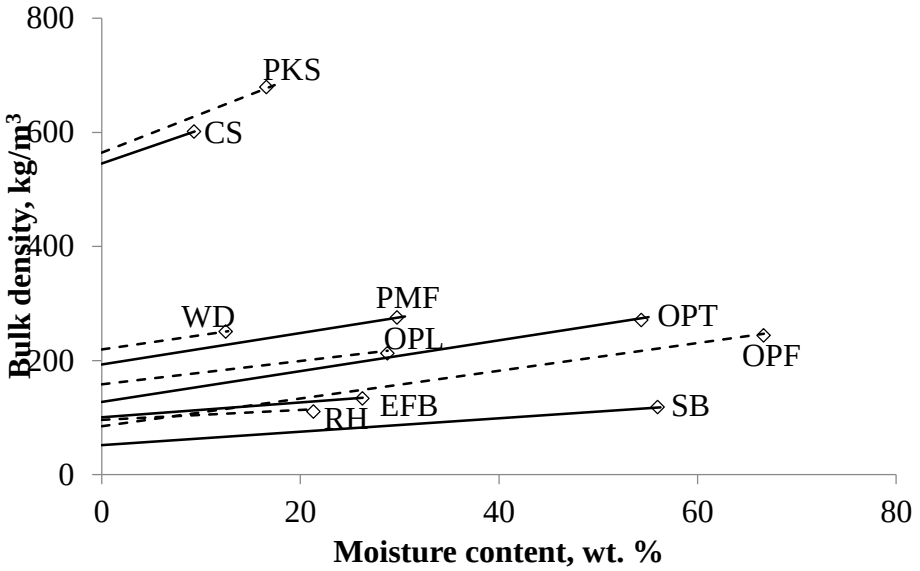

Figure 6. density-moisture content relations of selected Malaysian biomass residues

Table 4. The model correlations and their regression statistics

Residues	Model correlation	R^2	Adj. R^2	SER, kg/m^3
OPF	y = 2.4318x + 84.638	0.9983	0.9982	1.8709
OPT	y = 2.6951x + 127.64	0.9954	0.9952	2.7681
OPL	y = 2.0437x + 158.26	0.9605	0.9591	3.3914
EFB	y = 1.3055x + 100.58	0.9800	0.9793	1.5790
PKS	y = 6.7812x + 564.63	0.9983	0.9982	1.3195
PMF	y = 2.7466x + 193.31	0.9972	0.9971	1.2584
CS	y = 5.9998x + 545.54	0.9986	0.9986	0.5845
CF	y = 1.8472x + 150.91	0.9932	0.9930	0.9021
WD	y = 2.5003x + 219.51	0.9977	0.9976	0.4704
RH	y = 0.8553x + 96.125	0.7656	0.7575	2.2151
SB	y = 1.1771x + 51.897	0.9978	0.9978	0.9264

y=moisture content, wt. %; x=density, kg/m^3

Each sample was represented by 30 individual observations. All observations showed a linear reduction of density with a decreasing moisture content due to the loss of mass when water molecules were liberated from the samples during drying. Only PKS

and CS showed relatively high densities, more than twice in comparisons with other samples. This was due to the high density fibrous tissue packing and almost non-porous nature of the shell tissue structures in both PKS and CS for endospermic protection and retention functions, demonstrated by their ability to store water within them for a long period of time for preservation and germination purposes. All biomass samples other than PKS and CS showed a rather gradually declining pattern of density as a function of moisture loss. All linear models (with the exception of that for RH) were found to have R^2 and adjusted R^2 values of 0.9605-0.9986 and 0.9591-0.9986 respectively, showing a good fit and thus confirming the linear relationship between density and moisture content of the tested residues.

The relatively lower R^2 and adjusted R^2 values for the density-moisture content of RH, each at 0.7656 and 0.7575, indicated the low fit of the model due to the large variances between the density and moisture content values of RH, most likely attributed by the irregular pattern of mass loss in RH during drying. Inspections on RH samples used in the study did not reveal any abnormal feature of the samples i.e. clumping, bridging and voiding that may cause the irregular drying pattern. Further investigations led to a deduction that the reason for the irregular drying pattern may be attributed to the physical aspects of the container. The cylindrical container only had a top opening and this may have reduced the ability of the sample located near its bottom to lose moisture due to the ineffective capillary actions from the bottom up towards the exposed surface of the sample located on the top of the container. However, this problem was only observed in RH, therefore making it a specific and isolated case. The SER of the observed values showed a low range of between 0.4704-3.3914 kg/m^3, indicating the high accuracy of the estimations. Comparisons with the work by Guangul et al., Sulaiman et al., Moni et al., Simpson and Bakar et al. [18-21, 23] showed relatively high agreements of similarity in the density-moisture content relationship, thus confirming the validity of the linear models.

Model Validations

The representative examples of the linear regression and the line fit plot of the measured and predicted values for OPF are shown in Figure 7 (a) and (b) respectively, while the R^2, adjusted R^2, SER, AAE and ABE of the density-moisture content models of the tested biomass residues based on validation data are shown in Table 5. As shown below, most of the measured observations were found to closely follow the distribution trend of the predictions, albeit the existence of several outliers in the measured dataset. The R^2 and adjusted R^2 values of the model validations with the exception of that of RH showed a high accuracy of fitness with ranges between 0.9001-0.9725 and 0.8985-0.9715 respectively at a 95% confidence interval.

The regression analysis of the observed vs. measured values of moisture content in RH showed the R^2 and adjusted R^2 at 0.7712 and 0.7630, indicating a relatively lower data fit than the other samples, as also exhibited by those of its density-moisture content model. As earlier clarified, the noticeably lack of fit in the model and model validation may be attributed to the irregular drying pattern of the RH samples. This was verified in the comparatively high AAE of the RH model validation data at 92.2623%. The AAE of the other model validation data were found to be in the range of 8.3348-16.5096%. The SER of the model validation data were found to be within a small range, indicating the high accuracy of the estimates. The ABE analysis showed a mix of overestimations and underestimations, with the highest overestimation observed in the model validation data of RH, while the rest were within a moderate and agreeable range. The validation of the

models deduced that the entire density-moisture content models were accepted due to their high accuracy and reliability, with the exception of RH. Thus, the accepted models can be used to estimate the moisture content in the specific residues using density as a quicker alternative to the conventional and time-consuming oven drying method.

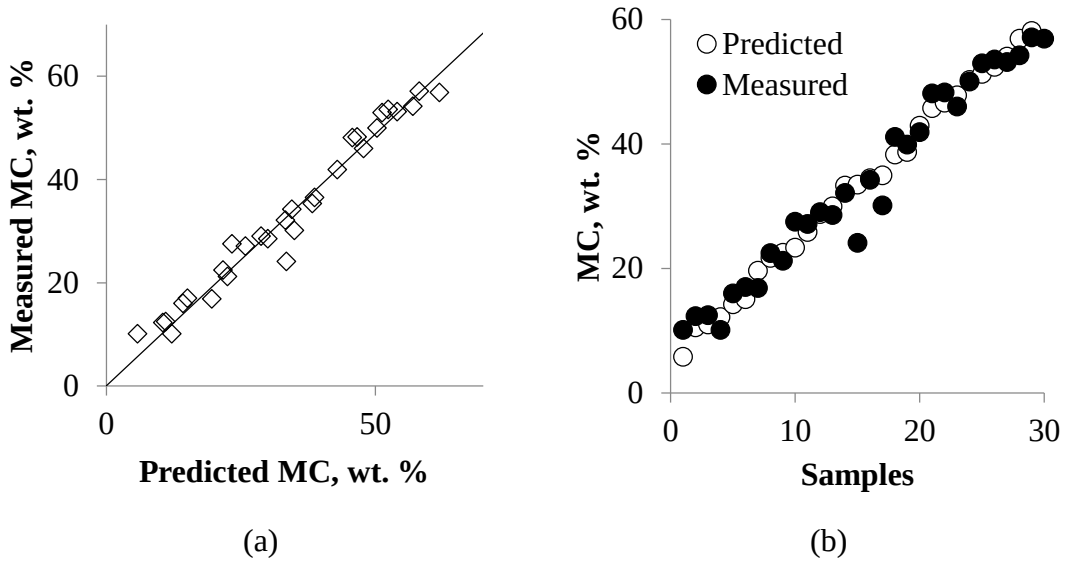

Figure 7. (a) Linear regression of the predicted and measured values of OPF moisture content and (b) data comparisons between the predicted and measured values of OPF moisture content.

Table 5. Regression statistics of density-moisture content model of selected Malaysian biomass residues.

Model	R^2	Adj. R^2	SER, wt. %	AAE, %	ABE, %
OPF	0.9699	0.9689	2.7361	9.1731	0.5227
OPT	0.9601	0.9587	2.9249	11.4774	-2.4603
OPL	0.9476	0.9458	1.2814	9.5861	-4.4997
EFB	0.9636	0.9623	3.1168	11.3725	-1.3174
PKS	0.9656	0.9644	3.0188	10.8536	-2.2674
PMF	0.9725	0.9715	1.7329	9.4076	-5.1643
CS	0.9001	0.8965	2.3994	8.3348	1.8739
CF	0.9167	0.9136	2.3959	12.0248	0.5544
WD	0.9091	0.9059	1.0352	9.8395	2.4316
RH	0.7712	0.7630	2.7359	92.2623	83.0750
SB	0.9578	0.9563	2.1067	16.5096	-12.4721

The time taken to determine the moisture content in biomass samples from their density was found to be in the range of 30-45 minutes, and was significantly quicker than using the oven-dry method that takes 24 hours to complete with a time saving of more than 95%. This means that the process of determining moisture content in biomass using the density-moisture content correlations is not only as accurate as using the conventional oven drying method, but the results can be derived much faster than using the latter method. Therefore, using the density-moisture content correlation to determine moisture

content in a specific biomass is highly recommended for an efficient and time-saving practice in utilizing biomass as raw materials for combustion or for other uses.

CONCLUSIONS

This study drew several conclusions as shown in the following:

i). All samples exhibited moderate to high moisture contents attributed to their nature of production, processing and storing conditions. The moisture contents were found to be removable up to 0.1% remaining moisture through artificial drying at 105°C for 24 hours;
ii). The equilibrium moisture contents (ECM) in all samples were found to be below 15% by weight except for CF. CF was assumed to contain a high amount of minerals that increased its hygroscopicity, hence having a relatively higher ECM than the other samples. A further investigation into this assumption is recommended;
iii). The hygroscopicity of all samples showed changes in mass of no higher than 10% when stored in an ambient condition with a temperature range of 23-26°C and humidity level of 70-80% for 48 hours. More observations in hygroscopicity in the samples for a longer storage period is recommended for better investigation;
iv). The relationship between the density and moisture content was found to be strongly positive linear in all samples. This was due to the reduction in mass when moisture was liberated from the samples during drying that, consequently, linearly reduced its density. The R^2 and adjusted R^2 of the linear fitting showed values of above 0.95 for all samples (except for RH), showing very high goodness of fit and confirming the existence of a linear relationship between density and moisture content;
v). The cross validations of the density-moisture content correlations models for all samples for reliability and accuracy analyses showed the R^2 and adjusted R^2 values of above 0.90 and 0.89 respectively at a 95% confidence interval (except for RH), showing high goodness of fit between the measured and predicted moisture content values. This concluded that the correlation models are accurate and reliable enough to predict the moisture content in biomass using only its density;
vi). The inaccuracy and unreliability of the correlation model for RH was assumed due to the irregular drying pattern observed in the samples, suspected due to the improperly ventilated drying container that prevented efficient drying and consequently affected the density-moisture content relationship. A retest using properly ventilated container is therefore recommended;
vii). The time taken in determining the moisture content in biomass samples using the correlation models was around 30-45 minutes as compared to the conventional oven-drying method that takes 24 hours, showing a significant time saving feature when using the correlation models;
viii). More data with random variations are required to increase their accuracy and reliability of the correlation models;
ix). Overall, the density-moisture content correlation models are found to be an accurate, reliable, energy-efficient and time saving tool to quickly determine moisture content in any specific biomass, and therefore are highly recommended for consumer and industrial users who work with biomass.

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