Optimization of bioresource material from oil palm trunk core drying using microwave radiation; a response surface methodology application

Parisa Amouzgar a, H.P.S. Abdul Khalil a,*, Babak Salamatinia b, Ahmad Zuhairi Abdullah b, A.M. Issam a

a School of Industrial Technology, Universiti Sains Malaysia, 11800 USM, Penang, Malaysia
b School of Chemical Engineering, Engineering Campus, Universiti Sains Malaysia, 14300Nibong Tebal, Penang, Malaysia

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ABSTRACT

In this study optimization of drying oil palm trunk core lumber (OPTCL) biomass using microwave radiation was reported. Optimizing of the drying conditions using microwave, avoid burning, shrinkage and increasing the permeability of OPT was aimed to develop a new value added material. A set of experiments was designed by central composite design using response surface methodology (RSM) to statistically evaluate the findings. Three independent process variables including time (2–10 min), sample weight (300–1000 g) and input power (660–3300 W) were studied under the given conditions designed by Design Expert software. The results showed the effectiveness of microwave drying in reducing the time and better removal of moisture as compared to that of oven drying with no significant changes. Employing optimum conditions at 6.89 min of time with a microwave power set at 4 for a sample of 1000 g, predicting 14.62% of moisture content.

1. Introduction

Drying of timber is an approach for adding value to sawn products from primary wood processing industries. If drying process is carried out immediately after the felling of trees, the timber can be protected against primary decay, fungal stain and attack by certain kinds of insects. Organisms, which can cause decay and stain, generally cannot thrive in timber with moisture content below 20%. The drying of wood concerns many researchers and timber companies around the world (Kueon, 2008; Vermaas, 1995). Nowadays, scientists focus on faster, cheaper and more effective drying methods. In traditional methods, it takes weeks and months for air drying, kiln drying and ovens, while with microwave it takes few minutes for the wood samples to reach the desired moisture content (Kueon, 2008). During the past 50 years, research has been conducted to investigate microwave drying of solid wood products but for microwave drying of oil palm trunk (OPT), no study has been reported so far.

In the preliminary study on microwave drying, the moisture content of OPT core part reduces from 294% to 12–15% which is within the optimum moisture content. The present study focuses on the core part of OPT which contains less vascular bundles and more parenchyma. Researches indicate that microwave drying with proper selection of power input, weight of drying material and drying time could increase the drying rate. As a result, it could save up to 50% of energy and significantly decrease volatile organic compound emissions when compared with the conventional drying methods (Guanben Du et al., 2005). In fact, microwaves can dry wood strands under lower temperatures and higher rates to produce dried wood with uniform and less moisture content and more permeability (Luntz, 2004; Torgovnikov and Vinden, 2002; Vermaas, 1995). It should suffer from less shrinkage and swelling, as compared to that produced by kiln drying and traditional methods which are much more time consuming and less cost effective (Guanben Du et al., 2005; Leiker and Adamska, 2004; Zhang et al., 1997). It can be concluded that although the microwave energy consumption is relatively higher than that of oven drying based on watt/h. Yet, considering much lower time will make the total energy consumed to be significantly lower than that of conventional methods.

In Malaysia, more than 40 million tons of waste from empty fruit bunches (EFB), oil palm trunks (OPT), and oil palm fronds (OPF) are generated annually (Abdul Khalil and Rozman, 2004). Oil palm trees generally have an economical life span of about 25 years and are replanted after 25 to 30 years (Khalil et al., 2009). During replanting, a large quantity of cellulosic raw material is generated in the form of felled trunks and fronds. It has been estimated that about 74 tons of dry oil palm trunks per hectare are generated during replanting. The annual availability of oil palm trunk is estimated to be around 13.6 millions logs per 100,000 hectares replanted. Under controlled processing conditions, this amount of logs could be converted into 4.5 million m$^3$ of plywood. Until now, only 20% has been used for the production of veneer for plywood and low quality kiln-dried lumber (Abdul Khalil et al., 2007). Insufficiency of wood lumber in the near future and potential for transforming oil palm trunk waste to an alternative wood lumber material make the research...
vital to find out alternative lumber material sources including waste materials. Preliminary research by the Malaysia Palm Oil Board (MPOB) demonstrated that the oil palm trunk could be engineered into a palm “wood” or solid oil palm trunk. As long as conventional drying methods used in their study caused drying defects such as high degree of shrinkage, checks, warping, twisting, and collapse with low recovery, and the processing cost was too expensive, their results were not promising so far (Khalil et al., 2009).

Response surface methodology (RSM) is a mathematical/statistical based technique which is useful for analyzing the effects of several independent variables on the response (Box and Draper, 1987). In most RSM applications, the relationship between the response and the independent variables is unknown. Therefore, the first step in RSM is to approximate the function \( f \). Usually, this process employs a low-order polynomial in some region of the independent variables. If the response is well modeled by a linear function of the independent variables, then the approximating function is a first-order model. If there is curvature in the system or in the region of the optimum, then a polynomial of higher degree must be used to approximate the response. This is to analyze and locate the optimum, i.e. the set of independent variables wherein the partial derivatives of the model respond with respect to the individual independent variables that equal to zero. The eventual objective of RSM is to determine the optimum operating conditions for the system, or to determine the region, which satisfies the operating specifications. Almost all RSM problems utilize one or both of these approximating polynomials (Khuri and Cornell, 1996; Mason et al., 2003; Montgomery, 2001). RSM has an important application in the process design and optimization as well as the improvement of existing design. This methodology is more practical compared to the approaches mentioned above as it arises from experimental methodology which includes interactive effects among the variables and, eventually, it depicts the overall effects of the parameters on the process (Ba and Boyaci, 2007). In this paper, the optimization of drying the oil palm trunk core with the assistance of microwave radiation is reported. A comparison between microwave drying with and without pre-air drying was also verified. For this purpose, a set of experiments were designed by central composite design using response surface methodology to statistically evaluate the findings. This study aimed to optimize the drying conditions using microwave to enhance a more complete drying, avoid burning, shrinkage and swelling and increase the permeability of OPT so it could be improved to a value added material (Khalil et al., 2009; Shulman, 2003).

2. Methods

2.1. Oil palm trunk preparation

Oil palm trunk (OPT) was obtained from Juru Plantation Sdn Bhd, Malaysia. The samples were directly cut to desired weight with a tolerance of ±2 grams (due to the even shape of the sample requirement) with a band saw (Model Hitachi A50). In the preliminary studies, the samples were used directly in a microwave drying process. The rest of the samples were first air dried at room temperature for 30 days to reach moisture content (MC) of 65 ± 2% prior to microwave drying. During the peeling process, the 10 cm diameter core was produced as waste and this central part of the OPT was used in this study.

2.2. Oven drying process

The samples with desired weights (as explained for microwave drying) and initial moisture of 294% w/w were oven dried (Constance; model FCH914446A) at 105 ± 3 °C to compare the effect of drying with microwave heat source. The drying time was varied between 2–10 min with the intervals of 2 min and the humidity was then measured.

2.3. Microwave drying process

Initially, in order to evaluate the amount of drying the oil palm trunk without pre-air drying, the samples were cut to achieve a weight of 1000 g and placed into the microwave (model WKS-4, Taiwan). The microwave power was set at level 5 corresponding to a power of 3300 w. The initial moisture of the samples was measured to be 294% w/w. The drying time was varied between 2–10 min with the intervals of 2 min and the humidity was then measured. Afterwards at microwave power level of 3 (1980 w), for 5 min samples weighing between 500–1000 ± 5 g were dried.

2.4. Moisture Measurement

For measuring moisture content in accordance with BS, EN323:1993, samples were cut to a cubic shape (2 × 2 × 2 cm), weighed with an analytical balance and dried in an oven of 103 ± 2 °C for 24 h.

2.5. Central composite design

In order to find out the best drying conditions using microwave radiation, a series of experiments were carried out by three chosen independent process variables including time, OPT concentration and input power. The design was carried out using 2^3 factorial experiments design with six star points (\( x = 0.5 \)) and six replicates at center points, according to the Central Composite Design (CCD). The ranges and the designed levels of the variables investigated in this study are given in Table 1. The moisture content after the drying process was taken as the response. The quadratic equation model for predicting the optimal point is expressed by Eq. (1).

\[
Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_i X_i^2 + \sum_{i=1}^{k} \sum_{j=i+1}^{k} \beta_{ij} X_i X_j + e
\]  

(1)

where \( Y \) is the response (dependent variable), \( \beta_0 \) is constant coefficient, \( \beta_i, \beta_{ij} \) and \( \beta_{ij} \) are coefficient for the linear, quadratic and interaction effect, \( x_i \) and \( x_j \) are factors (independent variables) while \( e \) is the error.

The Design Expert (Version 6.0.7, StatEase, Inc., USA) was used for regression and graphical analyses of the data obtained. Response surface methodology (RSM) was chosen as the method for the software to calculate the optimum value in the software. In general, a full-second order model was fitted to conclude the optimum combination of factor levels; this is the model including both linear and quadratic terms in each factor and all two-factor interactions (Eq. (1)) (Ryan, 2007). The variability in dependent variables was explained by the multiple coefficients of determination, R^2, while the model equation was used to predict the optimum values (Montgomery, 2001).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Coded levels of variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight, g</td>
<td>–1</td>
</tr>
<tr>
<td>Time, min</td>
<td>A</td>
</tr>
<tr>
<td>Input power, w</td>
<td>B</td>
</tr>
<tr>
<td>Weight, g</td>
<td>C</td>
</tr>
</tbody>
</table>

Table 1

Actual values and design levels of the variables.
3. Results and discussion

3.1. Microwave drying without air drying

Fig. 1 demonstrates the profile of moisture content of OPTCL dried using microwave radiation and oven drying. A comparison between these two methods shows the effectiveness of microwave drying in reducing the time and better removal of moisture. It is observed in the case of microwave drying that increasing drying time led to higher moisture content removal while the oven drying didn't show any significant change within the first 12 min. After 2 min of radiation, the moisture could reach 160% w/w showing 45.6% drying using microwave. It is also noted that initially the drying rate is higher in the first 6 min resulting to 79.6% drying. By extending time to 10 min, the drying rate decreases. It is noted that between 6 to 10 min only 8.8% enhancement in drying is achieved.

Fig. 2 demonstrates the moisture content of OPTCL without air drying using microwave radiation and oven drying with varying weights of sample. It is observed that decreasing the weight favored the moisture removal using microwave radiation. It is noted that the amount of moisture removed by microwave is almost 67% better as compared to the oven drying. The moisture content with oven didn't show significant change with varying the sample weight. The amount of moisture content removed varied by the sample size from 67.0% to 88.4% from 1000 to 500 g of sample in that order.

There are three distinct periods in microwave drying process, a warm-up period which can be characterized by quick rising temperatures and slow water loss; an evaporation period in which most water evaporates and the drying temperature reaches a plateau and a heating-up period in which moisture evaporation slows down and the surface temperature increases rapidly. A similar pattern of temperature and MC changes is observed for the convective drying process. During microwave drying, the warm-up period was shorter and the plateau temperature was relatively higher (boiling point of water), which could increase the drying rate. The warm-up period depends upon the energy input and the drying weight. In microwave drying the interactions of water molecules inside wood generate heat. When the drying temperature is close to the boiling point, the fast evaporation of water will cause a decrease in the sample's surface temperature, especially in the case of higher power input. This phenomenon was not observed during conventional oven drying processes (Guanben Du et al., 2005).

The higher input power results in the temperature increase at even higher moisture contents. Unlike the convective drying method, which relies on high surrounding temperature to transfer thermal energy, microwave drying generates the heat by oscillating polar molecules throughout the whole volumes of the drying materials. As drying begins from the inner part, less energy is wasted to increase the temperature of the surroundings (Oloyede and Groombridge, 2000). It was observed that in very low moisture contents (<30% w/w) without air drying burning occurred in the sample and in few samples, experienced shrinkage. In fact, lumbers shrink and swell with changes in moisture content. They are dimensionally stable when the moisture content is greater than the fiber saturation point (Forest Handbook, 1999). With careful drying, the right control of the humidity and the air movement, distortion can be kept to minimum. Air drying provides some times for wood samples to lose part of their moisture content and come to a balance with moisture content of the environment. When microwave drying took place after air drying, although the moisture content of samples reached below fiber saturation point of OPTCL (30% w/w), as they dried evenly shrinkage didn't happen.

Fig. 1. Moisture content of OPTCL without air drying by means of time using microwave radiation and oven with an initial concentration of 294%.

Fig. 2. Moisture content of OPTCL without air drying vs. sample weight using microwave radiation and oven drying: input power = 3, time = 5 min, initial moisture = 294%.
occurrence of drying defects prior to main drying stage (Luntz, 2004; Shulman, 2003).

The overheating of the lumber can be attributed to the parameters discussed in this research work. Over timing with a low weight in conjunction of high microwave radiation can lead to the burning of the lumber. This effect can be also detected in conventional drying of lumbers. As mentioned earlier, in conventional methods of drying other than the appropriate behaviors such as swelling and shrinking of the lumber are also observed (Shulman, 2003). These behaviors in the same conditions using microwave radiation were not observed which favors the use of microwave in drying lumbers (Luntz, 2004). Next, a series of experiments were designed using response surface methodology to optimize the microwave drying conditions.

3.2. Experimental design and analysis of variance (ANOVA)

The results at each point based on experimental design for microwave drying are shown in Table 2. A quadratic regression model was made by using actual values from the estimation of data. The model for microwave drying conditions is given in Eq. (2). The model was modified based on the insignificancy of some model terms.

\[
MC\% = +97.00339 - (12.99267 \times A) - (9.42279 \times B) - (0.054048 \times C) + (0.86780 \times A^2) + (4.80394 \times 10^{-5} \times C^2) + (0.28125 \times AB) \tag{2}
\]

The highly significant result at 99.99% of confidence level for moisture content was obtained. The coefficient of determination \(R^2 = 0.9918\) was also reasonably good. The remaining response (merely 0.8%) was therefore, explained by the residues. The significance of each coefficient in the Eq. (2) was determined by Student t-test and p-values as suggested by Montgomery (2001). The “Predicted R2” of 0.9774 is in reasonable agreement with the “Adjusted R2” of 0.9881.

The ANOVA for moisture content after drying OPTCL model was used to estimate the response as a function of time, input power and weight is shown in Table 3. The coefficient of variance of 7.99% for the model shows a good agreement between the data and the model. The “Lack of Fit F-value” of 1.59 implies that the "Lack of Fit" is not significant relative to the pure error. There is a 31.37% chance for the model that a "Lack of Fit F-value" of this large could occur due to noise. Non-significant lack of fit is good.

3.2.1. Overall evaluation based on model terms

In the analysis of data for moisture content of OPTCL after drying with microwave (Eq. (2)), a modified quadratic model is established. In this model, the first order and second order of all terms except for the second order of term B (input power) were signifi-

Table 2
Experimental design and results for microwave drying of OPTCL.

<table>
<thead>
<tr>
<th>Run</th>
<th>A Time, min</th>
<th>B Input power</th>
<th>C Weight, g</th>
<th>Moisture content, %</th>
<th>Observed</th>
<th>Predicted</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>1</td>
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</tr>
<tr>
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<td>10</td>
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<td>300</td>
<td>34</td>
<td>35.3</td>
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<td>3</td>
<td>2</td>
<td>5</td>
<td>300</td>
<td>19</td>
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</tr>
<tr>
<td>4</td>
<td>10</td>
<td>5</td>
<td>300</td>
<td>9</td>
<td>8.8</td>
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<td>1</td>
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<td>43</td>
<td>41.1</td>
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<td>2</td>
<td>5</td>
<td>1000</td>
<td>23</td>
<td>24.1</td>
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<td>10</td>
<td>5</td>
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<td>14</td>
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<tr>
<td>9</td>
<td>4</td>
<td>3</td>
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<td>20.7</td>
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<td>3</td>
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<tr>
<td>11</td>
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<td>2</td>
<td>650</td>
<td>18</td>
<td>20.0</td>
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<tr>
<td>12</td>
<td>6</td>
<td>4</td>
<td>650</td>
<td>7</td>
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<td>13</td>
<td>6</td>
<td>3</td>
<td>475</td>
<td>11</td>
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<td>12.3</td>
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<td>17</td>
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<td>3</td>
<td>650</td>
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<td>12.3</td>
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<td>6</td>
<td>3</td>
<td>650</td>
<td>14</td>
<td>12.3</td>
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</tbody>
</table>
The two-level interaction between all terms except for the interaction between terms A (time) and B (input power) was significant, while the other terms (interaction between terms AC and BC) were insignificant and omitted from the model. First level of all terms was at high level of significance (99.98%). All the other terms have considerable consequence with slightly less effects and high level of significance (>99.1%). It can be concluded that the data can accurately fit the model and the model can be used for the prediction of the variables within the given ranges.

3.3. Graph-based overall discussion

Fig. 3 demonstrates the response surface 3D plots indicating the effect of interaction between time and microwave input power (varying from 2–10 min and 1–5 unit, respectively) on the moisture content of OPTCL after drying, while holding the other parameter (weight) at its center point. It is noted that by increasing the power, more moisture was evaporated. This phenomenon is the main reason of using the microwave for drying wood. Yet, the energy consumption of microwave should also be considered. Thus, the input power of the microwave should be optimized with other parameters such as material weight and time. In overall, by increasing the time, the moisture content reduced to around 6 min of contact time reaching a moisture content of approximately 12%, and then slightly rose. This rise could be attributed to the equilibrium between the moisture content of air and wood at 6 min time in which the lumber starts to absorb the moisture from air (Shulman, 2003).

Fig. 4 reveals the interaction between time and weight on the moisture content of OPTCL after drying. In this figure, the second order effect of both terms is clearly observed. It can be noticed that by increasing the weight of the sample, the amount of remaining moisture increases. This can be attributed to the higher amount of moisture trapped in the sample which needs to be removed. The higher the amount of moisture in the sample the more energy and time are required to evaporate it. The moisture content of the sample as previously shown in Fig. 2 initially showed a decrease down to approximately 12% at 7 min of drying time. The figure shows that the best moisture removal occurred at 7 min of microwave time and a sample of approximately 500 g while the input power of the microwave was set at three.

**Fig. 5.** Response surface 3D plot indicating the effect of interaction between input power and weight on moisture content while holding the time at 6 min.

**Fig. 6.** Oil palm trunk core lumber (a) fresh sample before drying; (b) burned after drying; (c) shrunk; (d) well dried.
The 3D interactions between terms B and C are plotted in Fig. 5. It can be seen that both terms follow an almost linear trend. Increasing the weight led to the increase in moisture contents while the increase in the microwave input power favored the moisture removal of the sample. High input power and low weight could cause burning in the corners of the sample. Fig. 6(a) shows fresh OPTCL while Fig. 6(b) presents a picture of an OPTCL which has been over dried and burning of the lumber is clearly noted. This burning was due to the dehydration of the lumber. Fig. 6(c) is a sample with shrinkage and finally Fig. 6(d) shows a sample which has been dried properly.

As shown in the picture, uneven drying causes shrinkage in the samples and if the process is not properly controlled, the higher input power results in the temperature increase and burning in some parts of the samples. The well dried sample with the microwave was good in appearance and strength. In conclusion, the results obtained from the preliminary studies revealed the necessity of air drying before the microwave drying process for oil palm trunk. This has also been confirmed even with conventional drying methods, that air drying is required in advance of oven drying to achieve acceptable results (Luntz, 2004).

A set of solutions that were given by the software in order to determine the optimum conditions of moisture removal from OPTCL. These conditions were calculated based on the process ranges adjusted using Eq. (2) calculated by the software. The best given condition applicable in actual operating condition chosen is summarized in Table 4. These solutions were varied by performing the drying process under the predicted conditions. The parameters time and input power were adjusted to be in range while the increase in the microwave input power favored the moisture. The model suggested the best results at 6.89 min of time with a microwave power set at level 4 and 1000 g of sample. The microwave dried sample showed acceptable appearance, strength and permeability with improved mechanical and physical properties compared to fresh OPTCL and oven dried OPTCL.

4. Conclusion

This paper studied three variables on microwave drying of OPTCL using RSM. A mathematical model was suggested for moisture content as a response of microwave drying. This data could fit the equation with an R² of 99.18%. A set of optimum conditions were offered by the software to achieve around 14.28% of humidity. The model suggested the best results at 6.89 min of time with a microwave power set at level 4 and 1000 g of sample. The microwave dried sample showed acceptable appearance, strength and permeability with improved mechanical and physical properties compared to fresh OPTCL and oven dried OPTCL.

Table 4
Optimum condition suggested by the Design Expert software for the drying process.

<table>
<thead>
<tr>
<th>Run</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>Moisture content, %</th>
<th>Error S.D.</th>
<th>Obtained</th>
<th>Predicted</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.89</td>
<td>3.79</td>
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<td>14.62</td>
<td>14.28</td>
<td>0.34</td>
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* S.D. = Standard Deviation.