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COMPARATIVE STUDY ON THE DRYING OF OIL PALM SOLID WASTE USING CONVENTIONAL AND MICROWAVE METHODS

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Abstract

The purpose of drying is to reduce material humidity or water content. Several techniques can be used in the process, including conventional and microwave drying. Drying of oil palm solid waste aims to improve its physical properties. The study used a 10 g sample for each drying test. The drying process was performed on six variations of the drying temperature, i.e., 40, 45, 50, 55, 60, and 65 ℃. The temperatures used for heating started from ambient temperature to the predetermined drying temperatures, then it was held for 90 minutes. The measurement of the mass was performed every 20 seconds. Based on the result, it can be concluded that drying using a microwave oven gives higher effectiveness compared to drying using a conventional oven. The high drying temperature affects not only the drying rate constant throughout a constant time but also the drying rate constant during the falling rate period. For both methods, the drying rate has been found to be linearly proportional to the drying temperature. The increasing drying temperature will decrease energy intensity. There is no significant impact in the pore structure of drying products using microwave and conventional ovens at 65 ℃.

Keywords: Conventional drying, Drying rate constant, Energy intensity, Microwave drying, Oil-palm solid waste, Pore.

1. Introduction

Generally, drying is a process that aims to eliminate and/or reduce the water content of material using the thermal treatment. The drying process has been carried out for thousands of years with various methods that have been developed so far, such as solar drying (SD), hot air-drying (AD), freeze-drying (FD), vacuum-drying (VD), and osmotic drying (OD) [1]. In addition, there are also several other methods in the drying process, such as rotary drying, screw conveyor drying, multi-louver drying, and flash drying [2]. In general, for removing water content during the evaporation process, drying uses much energy as it requires a lot of heat [3].

There are thermal and non-thermal treatment methods in processing a material. Non-thermal treatments such as nitrogen ion implantation can change the surface properties of metals as surface roughness will increase with the increase of nitrogen ions doses [4]. Thermal treatment technologies that have been widely used are microwave and conventional technologies. In general, the purpose of a conventional or standard drying system is comparable to that of a microwave drying system, which is to encourage the release of the water content of a material. Conventional drying is comparatively simpler and has fewer controlled parameters than a microwave drying system [2]. The process of drying in a conventional system is to maintain the temperature moderately, exceeding the evaporation temperature of the water where it will evaporate and leave other volatiles. The microwave drying system mechanism depends on the absorber and the emitted microwave waves. Water is a microwave absorber compound that absorbs the energy of the microwave waves to be converted into thermal energy [5]. Recently, microwave drying has been widely used because it has several advantages, namely fast and efficient heating, environmentally friendly, and short reaction time up to 80% than conventional drying [6].

Palm oil is the world's most produced and consumed oil. Indonesia is the biggest palm oil producing country [7]. In 2018, the whole area of palm plantations in Indonesia reached 14,309,256 hectares, with a production capacity of 41,667,011 tons. By 2019, it is estimated that the palm oil products will reach 4.3 million tons increasing 1.5 million tons from 2018 [8], as a result of the elevated demand for Crude Palm Oil as a resource for vegetable oil and biofuel reserves. Along with the increasing area of oil palm plantations and palm oil production in Indonesia, by-products or waste also increases. The waste of palm oil industry is solid waste, i.e., Palm Kernel Shell, Oil Palm Fibers (Mesocarp Fiber/MF), and Empty Fruit Bunch [9]. Empty bunches, usually used as a substitution for mineral fertilizers, are applied directly in the industry through the composting mechanism [10]. Palm oil shell and fiber are usually for fuel, especially in boilers to generate steam and electricity. Oil palm waste has several characteristics, namely: high water content, low density, low calorific value, and hygroscopic properties (ability to absorb water from the environment) [7]. A process for converting oil palm solid waste into the biomass of high quality such as fuel or other products is therefore necessary. The process is called pre-treatment and one of the processes is drying.

So far, there have not been any researches related to the comparison of the drying process characteristics of palm oil industry solid waste (oil palm shell and fiber) using conventional and microwave methods. Microwaves can dry wood strands under lower temperatures and higher rates to produce dried wood with uniform and less moisture content and more permeability [11]. 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 [12, 13]. Amouzgar et al. [14] reported that 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. The drying kinetics of oil palm frond particles in a laboratory-scale agitated fluidized bed dryer was investigated under various operating conditions was conducted by Puspasari et al. [15]. The results indicated that inlet air temperature significantly affected the drying rate, followed by superficial air velocity and bedload. Nadhari et al. [16] reported that free moisture with a small bonding force could probably first evaporated out in the drying process, whereas the pore bound moisture with stronger bonding force required more energy to release out. These experiments were run at two different conditions for comparison between open-air fan drying and controlled atmosphere. The present work aims to investigate the drying characteristics of conventional and microwave ovens on oil-palm shell and fiber. This can be taken into consideration in the selection of drying methods for the industrial scale.

2. Experimental Section

2.1. Material

The research used solid raw material, namely oil-palm shell and fiber. The materials were obtained from palm oil industry waste in Riau, Indonesia. The raw material tested for drying was in the form of intact materials obtained from the plant. The proximate analysis of the biomass raw material was done compliant with the ASTM D7582-12 and the result shown in Table 1. About 10 g of oil-palm shell or fiber was used in each experiment. The sample used was material obtained directly from the industry in September 2019 with an average size of around 5 mm oil-palm shell diameter and 10 mm oil-palm fiber length, without prior processing.

Table 1. Proximate analysis (wt%) of biomass raw material.

Material	Moisture Content	Volatile Matter	Ash	Fixed Carbon	Density
	(%)	(%)	(%)	(%)	g/cm^3
Oil-Palm Shell	6.3769	67.7699	1.4987	24.3545	0.78
Oil-Palm Fiber	7.3736	63.4877	6.2404	22.8983	0.6

*air dry based

2.2. Experimental apparatus and procedures

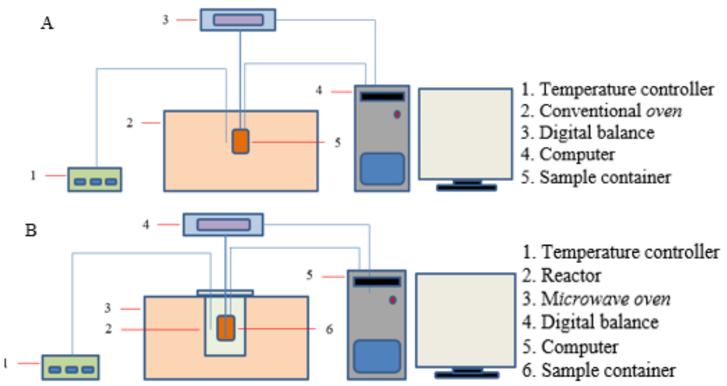
The tests were conducted by using a microwave and a conventional oven (Table 2). Electronic balance (Capacity: 0.25 kg, Precision: 0.0001 g) was located on the top of the oven. Weight data were collected and recorded by a data acquisition system during the experiment.

Table 2. Oven specification.

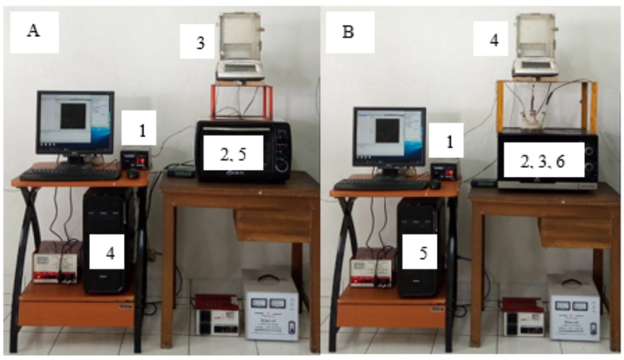
Specification	Conventional Oven	Microwave Oven
Power	800 W	800 W
Frequency	-	2.45 GHz
Brand and series	Kirin KBO-190RAW	Electrolux EMM2308X

An open Pyrex reactor (300 mm height, 100 mm ID) was used in the microwave drying. The sample was placed in a sample container made of Pyrex with a capacity of 100 ml. The process of drying was carried out at input power 800 W. A sample of 10 g [17, 18] was inserted at room temperature and heated until it reached the drying temperature and held for 90 minutes. The tests were carried out with temperature variations of 40, 45, 50, 55, 60, and 65 °C. These temperatures were chosen because they do not damage the material properties but increase their physical properties. The solid inner structure of the dried product was damaged over-drying. This damage was more severe at higher operating temperatures [19]. Several researchers using the drying temperature around it, such as Puspasari et al. [15] investigated the drying of oil palm frond particles under three various temperatures (50, 60, and 80°C). Boubekri et al. [20] conducted the experiments in a laboratory solar drier under temperatures oscillating around 50°C and 60°C, and Falade and Abbo [21] investigated the influence of variety and drying temperature range of 50-80°C on an air-drying pattern of date palm fruits.

The schematic diagram of the system is shown in Fig. 1. The temperature was set by using a temperature controller that turned off the electric current when the oven temperature reached the drying temperature and turned on the electric current when the oven temperature was below the drying temperature.



(a) Schematic diagram of experimental set-up of conventional dryer (A) and microwave dryer (B).



(b) Pictorial view of conventional dryer (A) and microwave dryer (B)

Fig. 1. Schematic and pictorial view of both types of dryers.

Microwave ovens work using electromagnetic waves that can penetrate materials and excite molecules evenly (not only on the surface). The heating process can take place selectively because microwave heat distribution only affects material that has microwave absorber properties such as fixed carbon [22].

The microwave heating process occurs quickly due to the excitation that causes heat to emerge from the body of the material. The heat spreads radially to all material parts in contradiction of conventional heating systems where the conventional heating takes place through a mechanism of radiation, convection, and conduction in which the temperature at the core of the material will warm up at the last moment Fig. 2.

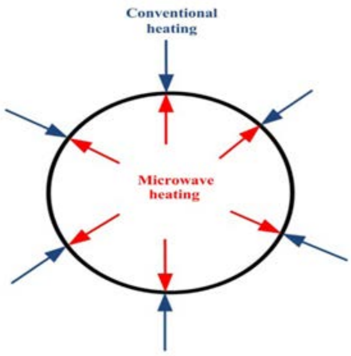


Fig. 2. The difference in the heating process using conventional heating and microwave [23].

After data were collected, the analysis of the drying rate was performed. During the period of constant rate, the amount of surface water was available to evaporate into the surrounding. The moisture content decreased continuously. The value of moisture content as defined in Eq. (1), the derivative of Eq. (2).

$$\frac{dM}{dt} = -k$$

$$\int dM = \int -k\, dt \tag{1}$$

$$M_t - M_0 = -kt$$

$$M_t = M_0 - kt \tag{2}$$

When the amount of water is enough to evaporate continuously, the drying rate decreases steadily, called a constant rate period. It is presumed to be equal to the difference of water content at each drying time (Mt) and equilibrium moisture content (Me), as written in Eq. (3), based on the Newton model [5]. The MR as the dimensionless moisture ratio can be calculated using Eq. (4), which is the derivative of Eq. (3). During the falling rate period, the drying rate value is constant, determined by Eq. (5) derived from Eq. (4) [23]. The value used to calculate the moisture content throughout the drying in the falling rate period is written in Eq. (6).

$$\frac{dM_t}{dt} = -k(M_t - M_e) \tag{3}$$

$$MR = \frac{(M_t - M_e)}{(M_0 - M_e)} = e^{-kt} \tag{4}$$

$$ln\frac{(M_t-M_e)}{(M_0-M_e)} = -kt \quad (5)$$

$$M_t - M_e = (M_0 - M_e).e^{-kt}$$

$$M_t = (M_0 - M_e).e^{-kt} + M_e \quad (6)$$

After the drying process, these selected specimens were gold-sputtered and examined under a field emission scanning electron microscope (SEM) (Zeiss EVO LS 10; Carl Zeiss) at 10.0 kV. The SEM photomicrographs were made with 2000 magnification for visual inspection.

3. Results and Discussions

3.1. Drying characteristic

Referring to Fig. 3, it is seen that the drying using a conventional oven resulted in various drying characteristics depended on the drying temperature. The drying characteristics of the oil-palm shell and fiber were similar. The lowest final mass happened at 65 ℃ followed by 60, 55, 50, 45, and 40 ℃.

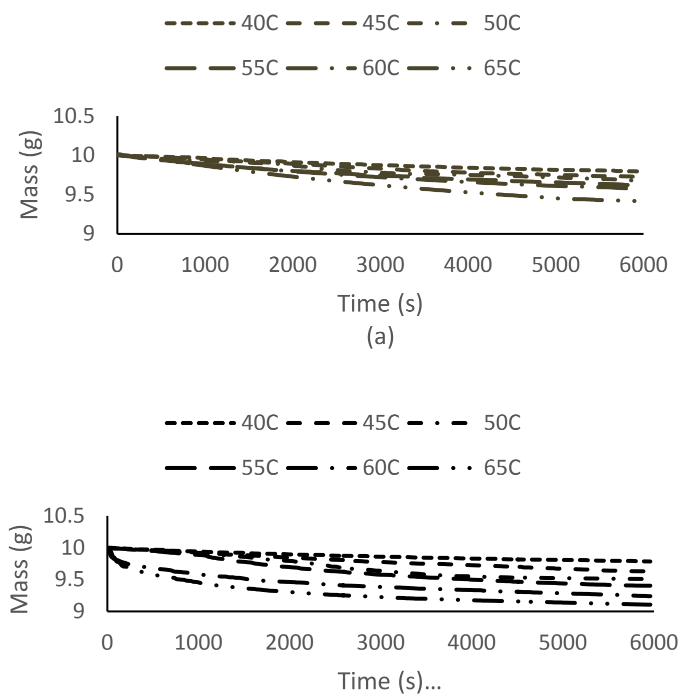


Fig. 3. Drying curves of palm oil shell: (a) conventional, and (b) microwave.

Referring to Fig. 4, it is seen that drying using microwaves produced different characteristics depending on the given drying temperature. The lowest final mass was achieved at 65 ℃ drying temperature followed by 60, 55, 50, 45, and 40 ℃.

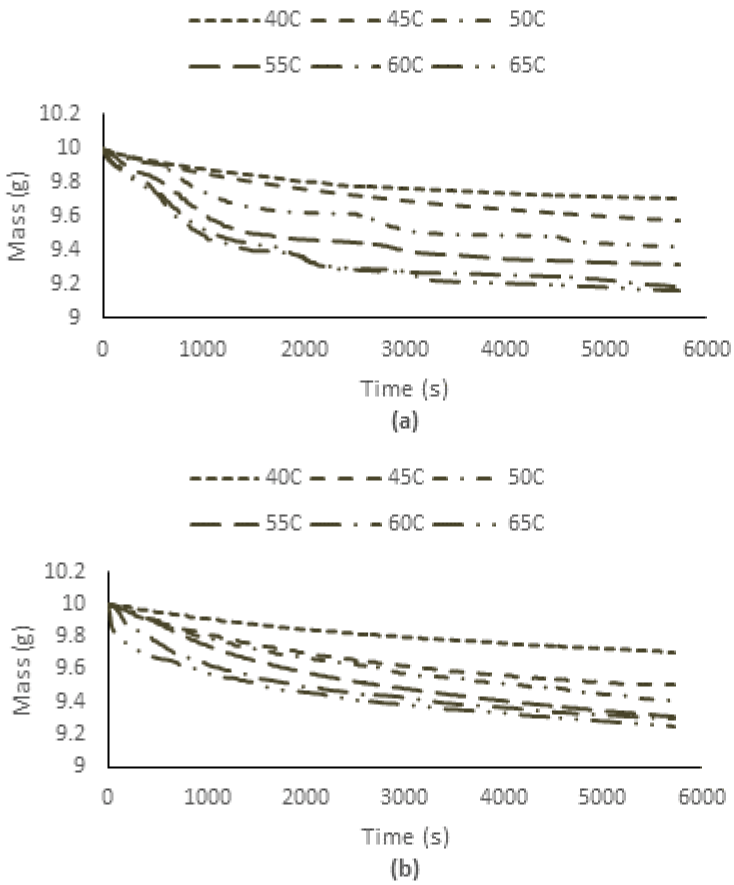


Fig. 4. Drying curves of palm oil fiber: (a) conventional, (b) microwave.

In general, the drying process is divided into four stages. The first stage is preheating. It takes a fast operating time. The material temperature in the preheating increases rapidly. The second stage is the constant drying rate. In this stage, the moisture on the material's outer surface evaporates. The constant depends on how much heat is transferred to the material. The rate is likely more stable for a longer time when the method is constant. The third stage is the falling rate stage in which the moisture transfer from the material to the surface occurs through the mechanism of molecular diffusion [5]. The fourth stage is the lag drying stage.

In order to obtain a more comprehensive comparison, drying characteristics of microwave and conventional ovens are plotted at given the temperature of 60 ℃ for the oil-palm shell. Figure 5 shows that there are four stages in the drying process, namely preheating, constant drying rate, falling rate, and lag drying rate. In the oil-palm shell drying process, the use of microwave oven for all stages is faster than a conventional oven. When the drying process is done using a conventional oven, the outer part of the material will be heated first because the surrounding air by convection propagates in the direction of the spokes of the material. The process of heating from the outside resulted in the release of water molecules into the air around, which is started from the outside, followed by the removal of water molecules in the inner part toward the surface of the material.

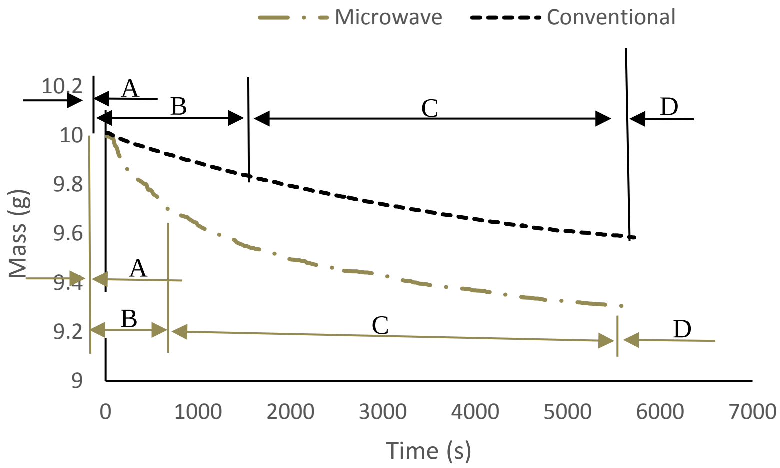


Fig. 5. Drying process of oil-palm shell using microwave and conventional oven at 60 ℃. A: Preheating, B: Constant drying rate, C: Falling rate, D: Lag drying rate

3.2. Model results

The model prediction compares satisfactorily with the experimental tests on the falling rate period using the conventional drying method; as an example, Fig. 6 shows this comparison at 60 ℃. The model was validated with drying data at the falling rate period, with the average deviation as 0.087 %. The experimental values were compared with the values calculated with the proposed model. At each time, the distribution of MC inside in the oil-palm shell was calculated according to the time drying using equation (6). The values of the MC agreed with the experimental ones, as can be observed in Fig. 6.

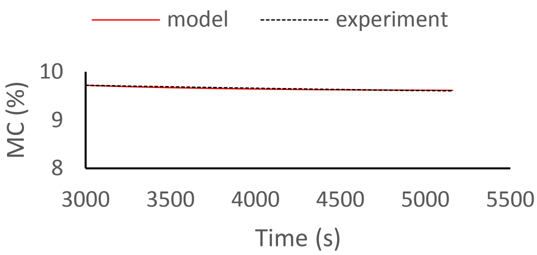


Fig. 6. Experimental and simulated curves for the falling rate period conventional drying of oil-palm shell at 60 ℃.

3.3. Drying rate

Figure 7 displays that the drying of the oil-palm shell and fiber using the conventional oven and the microwave oven showed different values of the drying rate. The drying process using a microwave oven showed higher rate than using a conventional oven. For both methods, the drying rate has been found to be linearly proportional to the drying temperature. The use of microwaves has an impact on the warming of the volumetric and the formation of steam. The generated heat causes the build-up of steam pressure internally that will push the water vapor out. This will decline the drying time significantly [24]. The phenomenon is different when the drying process is carried out using a conventional oven where the outer part of the material will heat first because the surrounding air by convection then propagates in the direction of the radius of the material. The process of heating from the outside resulted in the release of water molecules into the air that started on the outside then followed the removal of water molecules in the inner section toward the surface of the material. The average drying rate of oil-palm shell and fiber using a microwave oven gives a shorter drying time by 38.83%, and 40.15% compared that using a conventional oven. Drying by using a microwave oven causes a faster preheating and constant drying rate that using a conventional oven because in the heating process using a microwave oven, hot spots will form within the material. Generally, microwave drying will produce a drying rate of 25-90% higher than conventional drying [25-30]. The process of drying the shells using the conventional method at a temperature of 65 ℃ had a value of drying rate higher than fiber drying. This is possible because the drying process at high temperatures improves due to the effect of temperature on cell walls and tissue [31].

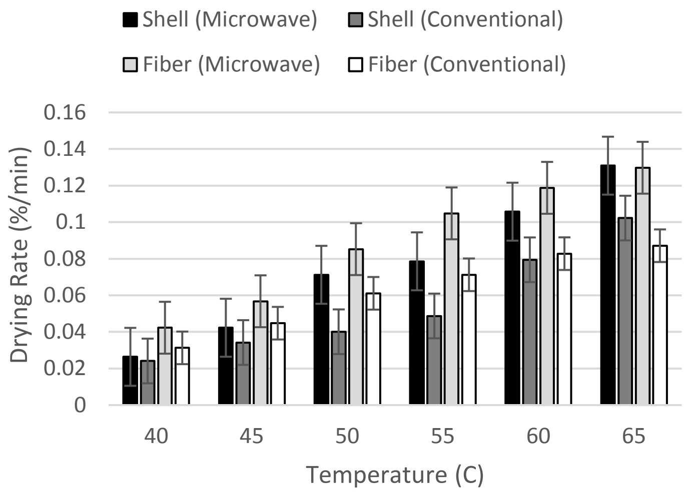


Fig. 7. Drying rate curves.

3.4. Kinetic compensation effect

3.4.1. Drying rate constant during constant period

A linear model that was determined by plotting M_t-M_o versus t for microwave drying of the oil-palm shell at 60 ℃ is shown in Fig. 8; the results suggested that the data were well fitted by the gained linear models. Indeed, the plot of M_t-M_o versus t significantly matched the linear model. Since the R^2 of the linear models in Fig. 8 is all larger than 0.70, it is proved that the drying mechanism fits well for the oil-palm shell, respectively. It was obtained that apparent Drying Rate Constant

During Constant Period (*k*) of the oil-palm shell was 0.0675 %/s, respectively. The value of k is shown in Fig. 9.

Figure 9 shows the drying rate constant the during constant period using the conventional and microwave ovens, and the drying rate is consistent with the rise in drying temperature. The drying process using a microwave oven generates drying rate constant, which is larger compared to that using a conventional oven. It means that the drying process using a microwave oven is more effective than using a conventional oven. The drying rate constant indicates the drying process speed until it reaches a critical point before it decreases. The higher the k value shows the moisture losses from the material [32].

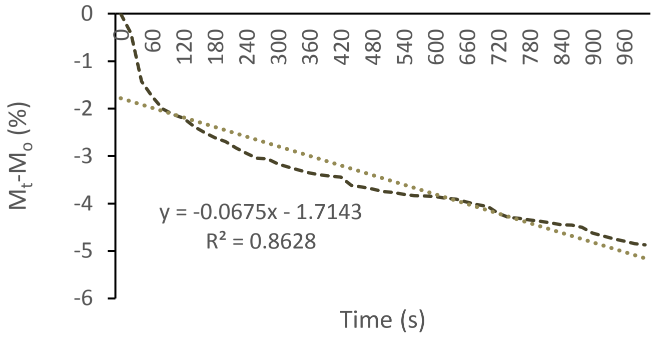


Fig. 8. Plot of Mt-Mo vs t of microwave drying of oil-palm shell at 60 ℃.

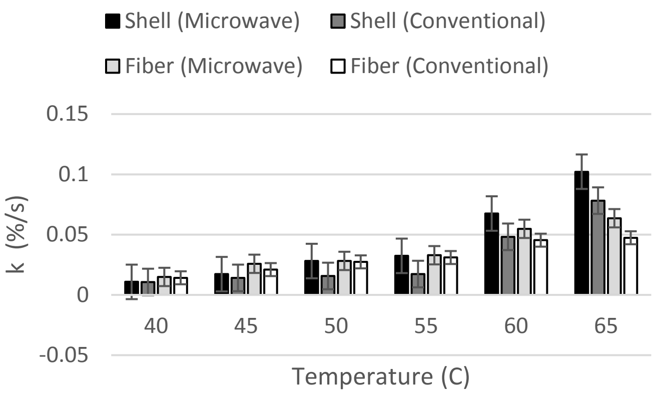


Fig. 9. Drying rate constant during constant period.

3.4.2. Drying rate constant during falling rate period

The k value of the drying rate throughout the falling rate period was defined by equation (5) built upon Newton's Law of cooling as a mass transfer approach [33]. Figure 10 shows that the use of microwave and conventional ovens will have an impact on different drying rate constants. The decrease of the drying rate constant using a microwave oven (average 0.0027%/s) is greater than that of the conventional oven (average 0.0020 %/s). The drying temperature also affects the value of the drying rate in the falling rate period. It is detected that for both methods, the drying rate constant during the falling rate period has been found to be linearly proportional to the drying temperature.

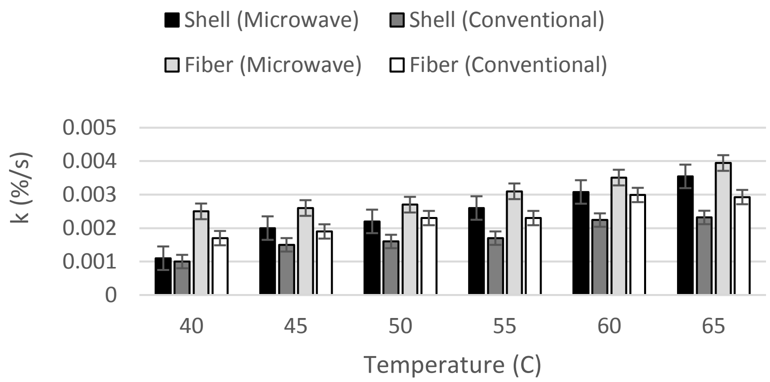


Fig. 10. Drying rate constant during falling rate period.

3.4.3. Energy intensity

Figure 11 shows that the increasing drying temperature will decrease the energy intensity value. The value of energy intensity in the oil-palm shell drying process using a microwave oven (average 752,374 J/% MC) is lower than that using the conventional oven (average 843,003 J/% MC). It is maybe due to the maximum temperature that takes place in the center of the material when using a microwave oven. It will trigger the drying process started from the center of the material, so the drying process in the oil-palm shell will be faster than that using conventional ovens.

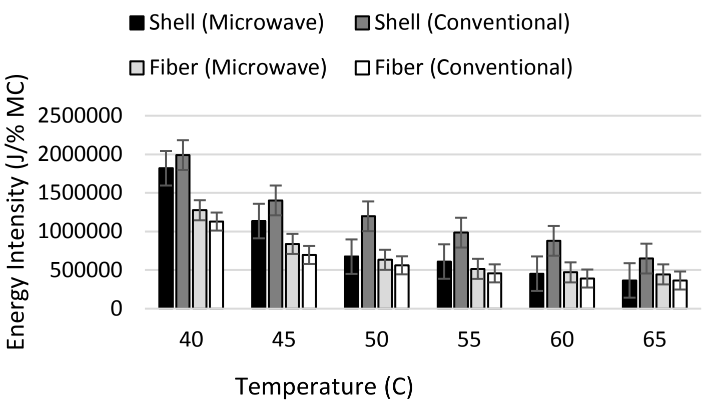


Fig. 11. Energy intensity.

The energy intensity value in the oil-palm fiber drying process using a microwave oven is almost the same as using a conventional oven. This is possible because of the influence of material size, so the use of a microwave oven in the drying of small size biomass such as oil-palm fiber will not have a significant impact compared to the conventional oven.

3.4.4. Surface morphology

The scanning electron micrograph in Fig. 12 shows the botanical pores on the surface of the oil-palm shell. Micrographs on the surfaces of an oil-palm shell dried in the microwave oven are shown in Fig. 12(b) and those in the conventional oven are Fig. 12(c). The oil-palm shell was dried at a temperature of 65 ℃ with a holding time of 1.5 h. For the rudimentary pore structure of the oil-palm shell in Fig. 12, a fraction of the voids is completely open while the others are in an intermediate phase and accumulated with deposits (arrow), especially on drying using microwave and conventional ovens. These deposits are the products of thermal decomposition and migrated from the internal structure [34]. The morphology examination shows no significant difference in pore structure in drying products using microwave and conventional ovens.

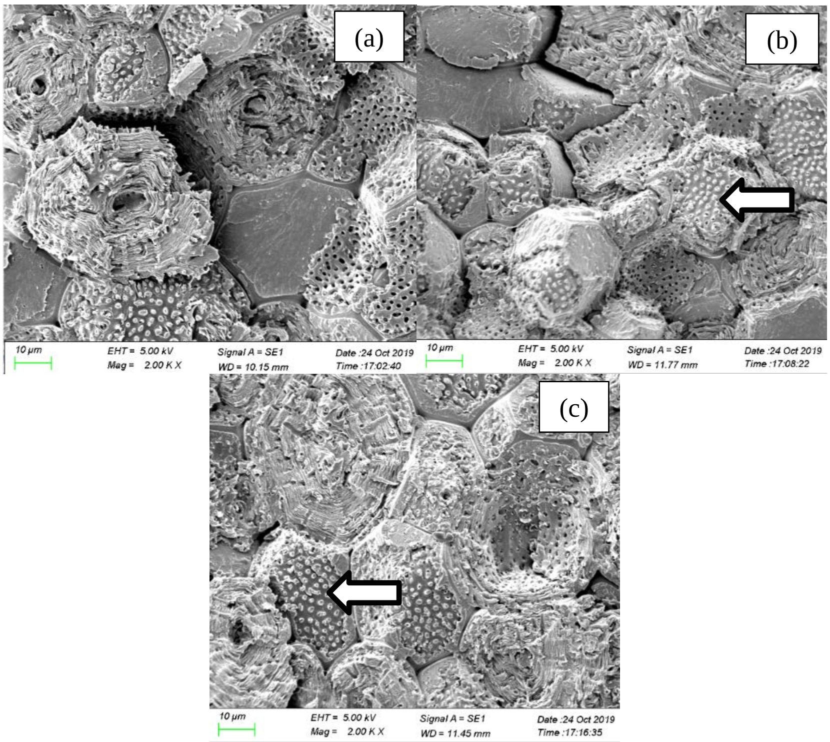


Fig. 12. Surface morphology structure of oil-palm shell (2000x):
(a) non treatment, (b) microwave drying, (c) conventional drying at 65 ºC.

3.5. Up-scaling

Conventional drying often requires much more time consuming and less cost-effective [12, 13], microwave drying can provide many advantages from an industrial point of view. Microwaves have large-scale commercial applications as processing technology and will provide a fast return on capital investment. Increased production efficiency and low maintenance costs can be achieved on a commercial scale [35].

Based on the data, the average drying rate of oil-palm shell and fiber using a microwave oven give a shorter drying time by 38.83%, and 40.15% compared that using a conventional oven. Energy intensity in the oil-palm shell drying process using a microwave oven (average 752,374 J/% MC) is lower than that using a conventional oven (average 843,003 J/% MC) or 10,63% more effective. It means that the use of microwave ovens on an industrial scale is possible.

4. Conclusions

The kinetic study of oil-palm shell and fiber drying using microwave and conventional ovens was carried out to study the comparison of drying characteristics. Drying using a microwave oven causes lower preheating time, constant drying rate, falling rate, and lag drying rate in comparison to that of a conventional oven. The increasing drying temperature impacts on the increased value of the drying rate constant in both constant and falling rate periods. The average drying rate of oil-palm shell and fiber using a microwave oven shows a shorter drying time by 38.83% and 40.15% compared to that using a conventional oven. Increasing drying temperature will decrease energy intensity. There is no significant difference in pore structure in drying products using microwave and conventional ovens at 65 ℃. Based on the simulation studies and experimental results that becomes similar to the average deviation as 0.087%, it can be concluded that the Newton model could predict the drying rate curve when compared with the experimental data point for the drying process as long as the falling rate period.

Nomenclatures

Dt	Difference of time, s
dM	Difference of water content, %
ID	Inner diameter, mm
k	Drying rate constant, %/s
MC	Moisture Content, %
M_e	Equilibrium moisture content, %
M_o	Initial mass, g
MR	Dimensionless moisture ratio
M_t	Water content at each drying time, %
t	Time, s

Abbreviations

AD	Hot Air-drying
FD	Freeze Drying
MF	Mesocarp Fiber
OD	Osmotic Drying
SD	Solar Drying
VD	Vacuum Drying

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