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Research article

Single and combined effects of ohmic and microwave heating on crude palm oil quality and stability

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Abstract

Pretreatment is a process that affects the extraction efficiency and the quality of crude palm oil (CPO). In this study, ohmic combined with microwave heating was used to pretreat oil palm fruits. The effects were evaluated of the pretreatment methods on the free fatty acids (FFA) content, peroxide value (PV), β-carotene content and energy consumption. The experiment was divided into two parts. First, either ohmic or microwave heating was used to pretreat samples. The microwave processing time was much shorter but the process required twice as much energy than the ohmic pretreatment. There were no differences between the yield and quality of the CPO obtained from the ohmic-pretreated and microwave-pretreated samples. However, when the samples were pretreated using ohmic heating followed by microwave heating, the FFA content of the CPO was lower than that pretreated using either ohmic or microwave heating (1.54% weight per weight [w/w], 1.70% w/w and 1.8% w/w, respectively) and was still lower than the critical limit even after storage for 8 wk. Furthermore, the combined process produced a slightly higher CPO yield than the single process (47% w/w and 46% w/w) while consuming 20% less energy than that required for the microwave process.

Introduction

Pretreatment of oil palm fruits is an important process in palm oil production, with the main objective of the process being to soften the outer shell or mesocarp of the fruits to enhance the extraction yield and to inactivate the enzymes that affect the crude palm oil (CPO) qualities (Cheng et al., 2011; Lim et al., 2015). Two key indices that affect the CPO quality and stability are the free fatty acid (FFA) content and peroxide value (PV). FFAs are products of the hydrolysis reaction of oil and can be used as an indicator for the evaluation of pretreatment process efficiency (Vincent et al., 2014). A proper pretreatment process can help to improve CPO quality because the formation of FFA is accelerated by lipase which can be inactivated by heat (Ngando et al., 2006). The PV is an indicator of the beginning of rancidity (sometimes called lipid peroxidation or oxidative degradation) and is strongly related to the FFA contents in the oil sample and the storage time (Shahidi and John, 2010).

Heat treatment is an effective method widely used to control the FFA content and the PV value of CPO (Vincent et al., 2014). However, the traditional pretreatment method requires a large amount of energy and takes a long time. For example, it takes about 70–90 min at 131°C in the steaming process (Sivasothy et al., 2006). Besides steaming, heating in a hot air oven is another conventional method that is generally applied to pretreat oil palm fruit. Because of the long time and high heating temperature, the β-carotene content in CPO can decrease substantially (Alyas et al., 2006) and the process unavoidably consumes a relatively high amount of energy. An energy-free method such as sun-drying is possible but would require 7–10 days and would be heavily dependent on the environmental conditions (Lim et al., 2015).

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For years, microwave heating has been applied to pretreat oil palm fruits (Cheng et al., 2011; Tan et al., 2017; Tang et al., 2017). The advantage of this process is that it uses a dry and clean technology, with electromagnetic waves inducing the breakdown of lignocellulosic materials through molecular collisions caused by dielectric polarization (Aguilar-Reynosa et al., 2017). The movement of polar particles generates rapid heating and the process time is usually short. For example, Cheng et al. (2011) reported on microwave pretreatment for palm oil production finding that it required a much shorter processing time than a traditional method. They mentioned that microwave heating effectively controlled the FFA content to 0.26% within only 1 min of heating. This highlighted the ability of microwaves to control enzymatic hydrolysis in oil palm fruits. In addition, they found that the ratio of the shorter chain fatty acid (C12:0) in the CPO also increased with the microwave pretreatment time, resulting in a better flow characteristic of the CPO product at low temperatures. Though the microwave pretreatment required a much shorter processing time than a traditional method, the energy efficiency of the process was relatively low.

Ohmic heating is another rapid form of volumetric heating where electric current is passed into a foodstuff without requiring any heating medium because heat can occur inside the food due to its internal electrical resistance (Sakr and Liu, 2014). The process offers high energy efficiency (Varghese et al., 2014). The heating rate of the system is adjustable by the proper selection of the heating room (ohmic cell) size and the food ingredients. The possibility of using ohmic heating as a pretreatment method was reported by Pootao and Kanjanapongkul (2016). According to their report, the CPO yield and the quality were quite high while the energy consumption was relatively low. Nevertheless, ohmic heating is a wet heating process. There is a possibility that the ohmic-treated CPO still has a high moisture content which can accelerate the hydrolysis reaction of oil.

In order to improve the effectiveness and energy efficiency of the pretreatment process, the current study investigated an innovative process (ohmic heating combined with microwave heating) to pretreat fresh 'Tenera' oil palm fruits, with an expectation that ohmic heating could improve the energy efficiency of the process while microwave heating could remove excess water and prolong the shelf life of the extracted CPO.

Materials and Methods

Oil palm fruit collection

Fresh ripe 'Tenera' oil palm fruits were collected from an oil palm plantation in Nakhon Pathom province, Thailand. The ripeness of the fruit samples was determined from the color, which was specified to be mostly orange. The average weight (± SD) of one fruit was 14±1.8 g with an average diameter of approximately 2 cm. The hardness of the samples was measured using a texture analyzer (Lloyd, LR5K, UK) with a load cell of 500 N. Each pretreated sample was compressed by 7% of its original height to prevent the circular plate hitting the seed of the sample using a 35 mm circular plate at a speed of 60 mm/min. All chemicals used were analytical reagent grade and were purchased from Ajax Finechem (New Zealand).

One-step process: Ohmic or microwave pretreatment

The ohmic heating system consisted of a voltage regulator (0–250 V, 50 Hz), a rectangular, ceramic ohmic cell and a temperature controller equipped with a 3-wire resistance temperature detector platinum sensor. Approximately 300 mL of water was poured into the ohmic cell and preheated. Then, 150 g of oil palm fruit were placed into the preheated water and held at a constant temperature (60°C, 80°C or 100°C) for a specified time (2 min, 4 min, 6 min, 8 min or 10 min) under a constant voltage of 160 V. The heating conditions used were based on Pootao and Kanjanapongkul (2016) who indicated that the maximum yield of CPO was obtained when the ohmic heating conditions were 100°C for 8 min at 150 V. The maximum voltage was slightly adjusted to 160 V due to the better heating rate. After heating, the samples were immediately separated from the water and the excess water was removed using paper towel.

For the microwave pretreatment, a sample of 150 g of oil palm fruit was placed on a ceramic dish and heated in a microwave oven (Samsung, ME731KD, Malaysia). The heating conditions were based on Cheng et al. (2011). The microwave power was either 180 W or 800 W and the heating time was a maximum of 7 min. After heating, the temperatures of at least three fruits were immediately measured and recorded.

As a reference, the sample was also pretreated using a traditional method by heating at 100°C for 4 hr in a hot-air oven (Binder, RF115, Germany). To ensure that the oven was run with the highest energy efficiency, a thin layer of the sample (equal to the thickness of a single fruit) was placed on an aluminum tray which was suited to the oven's size.

Combined process: Ohmic heating followed by microwave heating

A sample of 150 g of oil palm fruit was ohmic preheated followed by microwave heating. The heating conditions and time were based on the results from the one-step process and the details are described in the results and discussion section below. The extracted CPO from the sample treated at the selected condition was stored at room temperature (25 ± 2ºC) for a maximum of 8 wk. During storage, at least three samples were randomly taken for the quality determination at weeks 1, 2, 3, 4 and 8.

Morphological examination

A sample was sputter coated with a layer of gold in a vacuum chamber. The morphology of the gold-coated specimen was analyzed using a scanning electron microscope (SEM; Philips, model X130, the Netherlands). The pore size was analyzed from the SEM image using the ImageJ software (Image J 1.42q, National Institutes of Health, USA).

Extraction of crude palm oil

The pretreated samples were cooled to ambient temperature (approximately 25°C) before the oil extraction process was conducted. The mesocarp of the samples was peeled and fed into a hand-operated screw-press extruder. The impurities were removed from the extracted

CPO using a 10 μm filter. The CPO yield and the average recovery percentage (both expressed as the percent weight per weight; % w/w) were calculated using Equations 1 and 2, respectively:

$$\text{Yield} = m_{\text{oil}} / m_{\text{mesocarp}} \times 100 \quad (1)$$

$$\text{Average recovery} = \text{Yield} / \text{Total oil content} \times 100 \quad (2)$$

where m_{oil} and $m_{mesocarp}$ are the mass of the extracted oil and the total mesocarp fed into the screw-press extruder, respectively, both measured in grams. The total oil content (56.67% w/w) used in Equation 2 was the value reported in Silvamany and Jahim (2015) (obtained using solvent extraction method). After extraction, the samples were immediately kept in dark-brown glass bottles and stored at room temperature (25±2°C) before the quality determination was performed.

Determination of crude palm oil qualities

Free fatty acids content

The FFA content was analyzed by titration using a method described by American Oil Chemists' Society (1993). An amount (5 g) of the CPO sample diluted in 50 mL of neutralized ethanol solvent was titrated with 0.1 N sodium hydroxide solution until the end point was detected. Phenolphthalein was used as the indicator. The FFA (expressed as the percent weight per weight; % w/w) was calculated using Equation 3:

$$\text{FFA} = 25.6 \times (V - V_B) \times N / m \quad (3)$$

where V and N are the volume and concentration of the sodium hydroxide solution, respectively, m is the mass of the sample used and V_B is the volume of the sodium hydroxide solution needed to titrate the blank sample (pure solvent).

Peroxide value

The PV of the extracted CPO was determined using a modified method described in Association of Analytical Chemists (2000). Approximately 3 g of CPO were dissolved in 25 mL of a mixture of acetic acid and chloroform (3:2 volume per volume) and 1 mL of saturated potassium iodide solution was then added. The sample was shaken for 1 min and kept in a dark room for 5 min. Then, 75 mL of distilled water was added and the mixture was titrated against 0.002 N of sodium thiosulfate using starch solution as an indicator. A blank was also titrated under the same conditions and the PV was determined using Equation 4:

$$\text{PV} = (A - B) \times N \times 100 / m \quad (4)$$

where A and B are the volumes of the titrant used by the sample and the blank, respectively, both measured in milliliters and N and m are the concentration of the titrant (measured as the molarity) and the mass (measured in grams) of the sample, respectively.

β-carotene content

The β-carotene content was determined using a method described by Fauzi and Sarmidi (2010). Approximately 0.1 g of CPO sample was dissolved in up to 25 mL isooctane. The diluted sample was then placed in a 3.5 mL quartz cuvette and absorbance readings were taken at 446 nm using an ultraviolet spectrophotometer (Shimadzu, UV-1800, Japan). The β-carotene (expressed in parts per million; ppm) was calculated using Equation 5:

$$\beta\text{-Carotene content} = 383 \times (a_s - a_b) \times V / (100 \times m) \quad (5)$$

where a_s and a_b are the absorbance at 446 nm of the sample and the blank, respectively, and V and m are the volume (measured in milliliters) and the mass (measured in grams), respectively, of the sample.

Energy analysis

The amount of energy consumed (measured in kilowatt hours per kilogram of palm oil; kW-hr/$kg_{palm\ oil}$) during pretreatment was calculated by comparing the total energy supplied to the system (Q_{in}; measured in kilowatt hours) to the total mass of oil palm fruits in one batch (m_p; measured in kilograms) using Equation 6:

$$Q_{in} = \Sigma(I \times V \times t) / 3{,}600{,}000 \quad (6)$$

where V is the instantaneous voltage, (measured in volts) and I is the electric current (measured in amps) supplied to the system and t is the heating time (measured in seconds).

Statistical analysis

All experiments were done with at least three independent replicates. Analysis of variance was performed to determine significance of treatment effects. Duncan's new multiple range test was used to compare means at a confidence level of 0.95 ($\alpha = 0.05$).

Results and Discussion

Effects of a single process

Hardness

One of the main objectives of the pretreatment process was to soften the mesocarp or pulp of the oil palm fruits to increase the efficiency of the subsequence stripping process. For a reference, the samples were also pretreated by dry heating in a hot-air oven at 100°C for 4 hr, as a traditional pretreatment method. The qualities of the CPO are shown in Table 1.

Two pretreatment methods (ohmic heating and microwave heating) were used to pretreat the oil palm fruits. Fig. 1A shows the effects of the ohmic pretreatment conditions on the hardness of the samples. The threshold level at about 12 N indicates that the separation of the mesocarp from the kernel has been efficient if the hardness of the sample is lower than this value (Panich et al., 2013).

At 60°C, all samples were still too hard, even though they were heated for the maximum time of 10 min. Increasing the temperature to 80°C slightly decreased the hardness of the samples to about 2–3 N. The hardness of the samples rapidly decreased when the samples were heated at 100°C. These results agreed with Vu et al. (2004) who reported that thermal softening of carrot depended on the temperature and time of the preheating and the heating process. Kaur et al. (2016) explained the changes in cell structure and cell membrane were due to electroporation, staring from the building up of charges on the cell walls at low frequencies, leading to the pore formation in the cell membranes. The degree of the cell disruption was higher at a higher temperature or longer heating time. This could explain why the oil palm fruit became softer with increased temperature and heating time during ohmic heating.

Fig. 1B shows the effect of microwave heating on the hardness of the samples. The microwave power was a key factor that affected the hardness of the samples. Sample hardness slowly decreased following microwave heating at 180 W and reached the threshold level at the maximum heating time of 7 min. At a microwave power of 800 W, the hardness of the sample rapidly decreased at the beginning of the heating process. The hardness was below the threshold value at 3 min. During the heating process, the microwaves caused localized superheating inside the sample, known to be a specific effect of microwaves (Mello et al., 2014). This resulted in a rapid increase in the product temperature and shortened the process time. With longer heating times of 5 min and 7 min, the surface temperatures increased to 114±3°C and 126±5°C, respectively. Consequently, the surface of the samples became dried and burned, and the hardness increased to greater than 30 N in both cases.

The softening of the samples was related to pore formation on the sample surface. SEM images in Fig. 2 show the pore formation on the surface of samples after ohmic heating at 160 V for different times. At a holding time of 0 min, the surface of the sample was still closed (Fig. 2A). When the holding time was longer, not only the number of pores (data not shown) but also the average pore diameter increased. When the holding time increased from 2 min to 8 min, the average pore diameter expanded from about 0.5 µm to 20 µm (Fig. 2B). However, increasing the holding time from 8 min to 10 min had little effect on pore formation and thus the hardness values of the samples heated for 8 min and 10 min were not very different. Similarly, for the microwave-treated samples, the pore formation on the samples was also observed from the SEM images (Figs. 2C and 2D). The pore size increased up to 3 min. After that, the heating time had little effect on the number and the average diameter of the pores. It should be noted here that the surface of the microwave-pretreated sample was much dryer than the ohmic-pretreated sample.

Table 1 Properties of crude palm oil extracted from samples baked at 100°C for 4 hr and energy consumption. Values given are means of three replicates ± SD

Property of crude palm oil extracted	Mean±SD
Hardness of oil palm fruits (N)	13.37 ± 1.87
Yield (%w/w)	47.11 ± 1.37
FFA content (%w/w)	1.44 ± 0.19
Peroxide value ($meqO_2$/kg)	1.37 ± 0.15
β-carotene (ppm)	404.50 ± 13.90
Moisture content (%w/w)	0.15 ± 0.04
Energy consumption (kW-h/$kg_{palm\ oil}$)	0.67 ± 0.01

N = Newton; w/w = weight per weight; $meqO_2$ = milliequivalent of oxygen; ppp = parts per million; kW = kilowatt

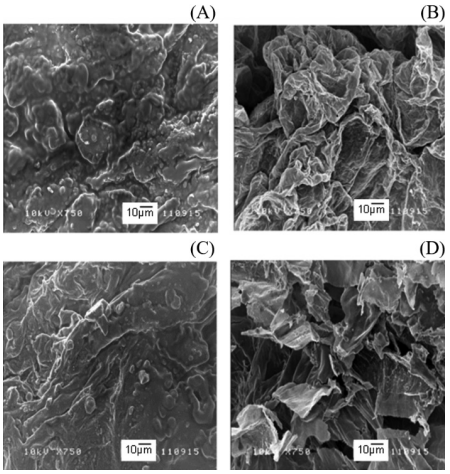

Fig. 2 Pores formation in oil palm fruit surface during: ohmic heating at 160 V and 100°C for (A) 0 min and (B) 8 min and microwave heating at 800 W for (C) 1 min and (D) 7 min, where scale bar = 10 µm

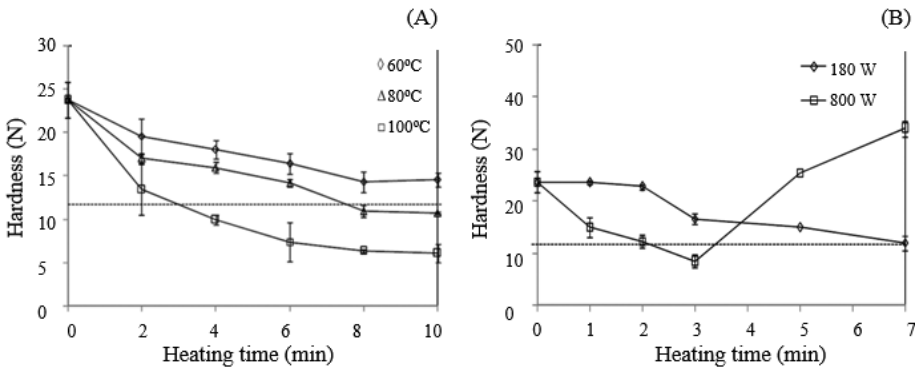

Fig. 1 Hardness of (A) the ohmic-heated samples at 160 V and (B) the microwave-treated oil palm fruits, where the horizontal dotted line represents the threshold level at approximately 12 N

Yield

Table 2 shows the yield of the CPO extracted from the ohmic-heated samples. The average recovery percentage was also reported. Clearly, temperature and holding time significantly affected the quantity of the extracted CPO. The maximum yield of 46.3% was obtained when the samples were pretreated at 100°C for 8 min. This could have been due to an increase in the number and the diameter of the pores that formed over the longer holding time and these enhanced the extraction process. An increase in the yield could have been due to the synergistic effect of ohmic heating and thermal treatment. During a conventional heating process, the cell internal pressure could increase due to water vapor in the cell until the cell disruption took place. With an additional effect of ohmic heating, cell electroporation could happen if the electric field were strong enough and this could cause many holes in the cell wall thus facilitating the extraction process, so the process time could be shorter and the recovery yield could increase. Pereira et al. (2016) reported the synergistic effects of an electric field and thermal treatment in their study on the effects of ohmic heating on the extraction of food-grade phytochemicals from colored potato; they mentioned that the maximum yields of anthocyanin and total phenolic compounds were obtained when the maximum electric field strength, temperature and time were used to pretreat purple potato.

However, in the current study, increasing the holding time to 10 min resulted in a decrease in the yield to 44.8%. It was observed that a small quantity of palm oil leaked from the samples to the water surface during ohmic heating if the holding time was longer than 8 min. This suggested that the maximum time should not be longer than 8 min.

Fig. 3 shows that the CPO yield obtained from the samples treated using microwave heating depended on both the microwave power and the heating time. While a linear relationship between the yield and the heating time was observed at the lower microwave power, the yield was nearly 40% when the heating time was only 1 min at a heating power of 800 W. However, the yield was constant when the heating time was longer than 3 min.

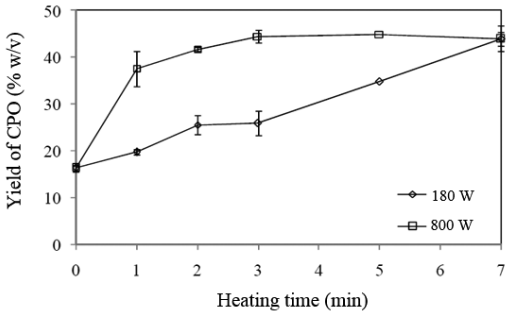

Fig. 3 Effects of microwave heating conditions on yield of extracted crude palm oils (CPO), where w/v = weight per volume and error bar = ± SD

Baryeh (2001) reported that the CPO yield depended strongly on the temperature, the heating time and the extraction pressure and found that the CPO yield obtained from samples pretreated at 100°C for 10 min increased from 3.5% to 47.0% when the extraction pressure was raised from 5 MN/m^2 to 35 MN/m^2 (50 bar to 350 bar). In the current study, the recovery percentage ranged from 55.9% w/w to 81.7% w/w depending on the heating conditions. From the fact that the extraction process involved a hand-operated screw-press extruder which provided a relatively low extraction pressure, the CPO yield could be higher than the values reported above if the extraction process were improved.

Free fatty acids

Fig. 4A shows the effects of temperature and heating time on the FFA content in the CPO extracted from the ohmic-pretreated samples. The fresh palm oil extracted from the fresh palm fruits contained an FFA content as high as 28% w/w. After ohmic treatment at 60°C, the FFA content decreased to about 5% w/w within 4 min. The results agreed with a previous study which reported that ohmic pretreatment at a relatively low temperature was sufficient to control the FFA content in CPO (Pootao and Kanjanpongkul, 2016). The temperature had a strong effect on the FFA content. At 100°C, the FFA content of samples suddenly decreased to 4.27% w/w and 2.94% w/w after heating for 2 min and 4 min, respectively. The CPO producing the minimum FFA content of about 1.7% w/w was treated at 100°C for 8 min. After 8 min, the FFA content decreased only slightly. From the statistical analysis, both factors (temperature and time) significantly affected the FFA content in the CPO extracted using the ohmic heating treatment. The effectiveness of FFA reduction could have been due to the process ability to inactivate lipase in mesocarp palm oil.

Ngando et al. (2006) studied the activity of lipase in palm oil mesocarp and reported that the lipase activity almost linearly increased when the temperature increased from 20°C to 45°C but decreased when the temperature was higher than 45°C. They also reported that lipase was not active at a pH below 7 or higher

Table 2 Yield of crude palm oil extracted from ohmic-pretreated samples (% weight per weight; %w/w) where numbers in parentheses indicate average recovery percentage (%w/w)

Temperature (°C)	Heating time (min)				
	2	4	6	8	10
60	31.7 ± 0.5^{eB}	34.2 ± 1.5^{dB}	37.2 ± 0.5^{cB}	39.7 ± 1.1^{bB}	42.0 ± 0.4^{aB}
	(55.9)	(60.3)	(65.6)	(70.1)	(74.1)
80	33.7 ± 1.5^{cAB}	36.5 ± 1.5^{bAB}	39.4 ± 1.6^{aB}	41.1 ± 0.9^{aB}	41.6 ± 1.4^{aB}
	(59.5)	(64.4)	(69.5)	(72.5)	(73.4)
100	35.9 ± 2.7^{bA}	38.6 ± 2.1^{bA}	42.6 ± 3.1^{aA}	46.30 ± 1.20^{aA}	44.8 ± 1.6^{aA}
	(63.3)	(68.1)	(75.2)	(81.7)	(79.1)

mean (± SD) values with different capital superscripts within each column and lowercase superscripts within each row denote significant ($p < 0.05$) differences between groups.

than 11.5. This suggested that the process might be an alternative way to reduce the FFA content by adjusting the pH condition of the CPO and to decrease the level of thermal treatment for better quality preservation. However, such investigation was outside the scope of the current research and would require further systematic study to verify this hypothesis.

Besides ohmic heating, pretreatment of oil palm fruit was investigated using a dry heating process. The ability of microwave heating to inactivate lipase has been confirmed (Keying et al., 2009; Patil et al., 2016). The current study indicated that the microwave power significantly decreased the FFA content in the CPO samples. For the microwaved samples treated at 180 W, the FFA content continuously decreased and reached the 5% w/w limit at 5 min, while the FFA content in the microwaved samples at 800 W reached this limit at the beginning of the heating process (Fig. 4B). The minimum FFA content was nearly the same as the value reported by Hadi et al. (2012) who treated oil palm fruits using microwave heating for a maximum time of 5 min and reported that the FFA content was between 1.02% w/w and 2.19% w/w.

In conclusion, the minimum FFA content in the samples microwave-treated at 800 W for 5 min was 1.3–1.4% w/w while it was 1.6–1.7% w/w for the 8-min ohmic treated sample.

Peroxide value

Fig. 4C shows the effects of the ohmic pretreatment conditions on the PV in the extracted CPO samples. Clearly, the temperature and holding time significantly affected the PV of the CPO samples. For the ohmic-pretreated samples at 80°C, the PV was effectively reduced to approximately 3.8 meqO_2/kg after a holding time of only 2 min. The minimum PV was 1.40 meqO_2/kg when the sample was treated for 8 min at 100°C. A decrease in the PV value could have been due to the applied voltage affecting enzyme inactivation.

Castro et al. (2004) studied the sensitivity of several important food-related enzymes toward ohmic heating and reported that the temperature, heating time and electrical field strength affected enzyme inhibition. Their results showed that the electrical field had an additional effect on the inhibition of lipoxygenases and polyphenoloxidase. They suggested that the action of the electric field on the metallic prosthetic groups of the lipoxygenases and polyphenoloxidase could have been the main reason that the enzymes were inactivated. Similar results of electric field strength on the inactivation of peroxidase (POD), a heme-containing enzyme, were also reported by Jakób et al. (2010) who demonstrated that POD inactivation was much faster under ohmic heating than under conventional heating.

Fig. 4D shows the effects of the heating time and the microwave power on the PV. At the low microwave power level, the PV linearly decreased with the heating time from 0 min to 5 min and then was nearly constant at about 2.1–2.6 meqO_2/kg. Increasing the microwave power to 800 W rapidly decreased the PV from the first minute of heating. As the microwave power increased, the internal temperature of the oil palm fruit increased and thus the lipase contained in the CPO was effectively inactivated. At the high microwave power level, the PV in the CPO sample reached the minimum value of about 1.3–1.4 meqO_2/kg after 3 min of the pretreatment process.

β-carotene

The *β*-carotene content in the CPO extracted from an unprocessed (fresh) oil palm fruit was about 650 ppm. The *β*-carotene content decreased to 459.5±26.4 ppm when the samples were pretreated using ohmic heating at 100°C for 8 min (data not shown). Compared to the conventional method, ohmic pretreatment could preserve the *β*-carotene content in the sample by about 12% (404.50 ppm, as shown in Table 1). The holding time and the temperature had strong

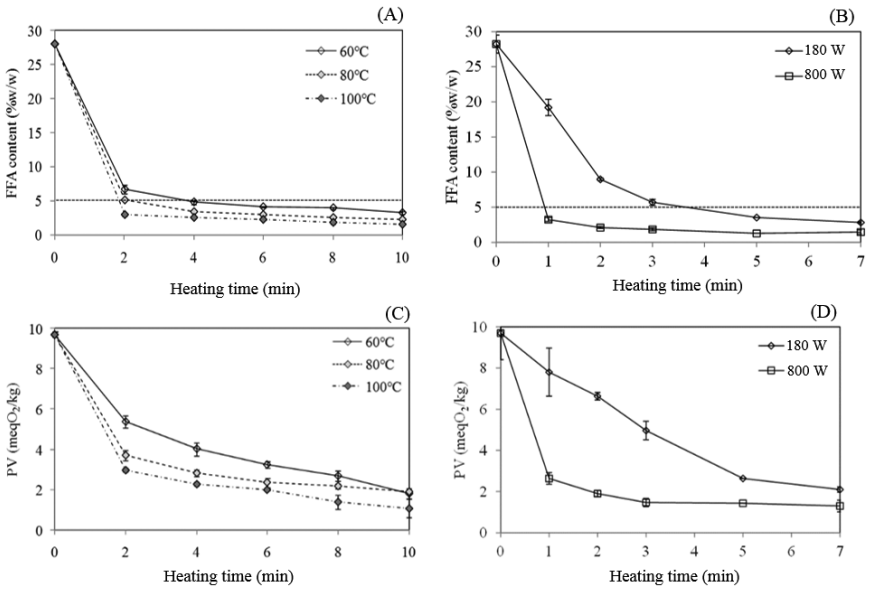

Fig. 4 Free fatty acid (FFA) contents in crude palm oils extracted from samples pretreated using (A) ohmic heating and (B) microwave heating and peroxide value (PV) of crude palm oils extracted from samples pretreated using (C) ohmic heating and (D) microwave heating, where w/w = weight per weight; meqO2 = milliequivalent of oxygen and error bar = ± SD

effects on the β-carotene content. This finding agreed with Alyas et al. (2006) who studied the effects of the heating temperature and holding time on the β-carotene content in red palm olein and reported the effects of the holding time and the heating temperature on the β-carotene content. For the microwave-heated samples, a continuous decrease in the β-carotene content was observed at the high level of the microwave power. The β-carotene content reached its minimum value of approximately 310 ppm when the samples were heated for 7 min at 800 W. From the measurements, the internal temperature of the microwave-treated samples for 7 min was much higher than that of the ohmic pretreated samples (126.0±5.0°C and 100.0±0.5°C). Thus, the difference in the internal temperature could have been a reason for the differences in the degree of carotene deterioration.

Though the average β-carotene content in the microwave-pretreated sample was lower than for the ohmic-pretreated sample, of note was that when the sample was microwave pretreated for 3 min at 800 W, its average β-carotene content was still higher than for the conventional-pretreated sample (413 ppm and 404 ppm, respectively, as shown in Table 1). In conventional heating, heat was transferred to the surface of the sample by convection, followed by conduction from the surface to the inside part of the fruit. This process required a much longer time to soften the mesocarp than for the microwave process (4 h and 3 min, respectively), making the oil palm fruit surface harder and drier, resulting in a greater decrease in the β-carotene content.

However, notably, the different result obtained using ohmic heating and microwave heating could have been due to the different surrounding conditions and heating mechanisms of the ohmic and microwave pretreatments. In ohmic heating, the samples were treated in a wet environment, while microwave heating could be considered as a dry heating method. For example, if samples were put in water or soaked with water before being heated in a microwave, the results would be different, as the process time could be slightly longer but the residue β-carotene content in the extracted CPO might be higher. Thus, the objective of the current study was not to determine which process was better or worse, but to demonstrate the advantages of each process and to explore the possibility of developing a combined process that could provide the highest benefit.

Combined effects of ohmic and microwave heating on yield and quality

As mentioned above, the sequence of the combined method used in this research started with ohmic heating followed by microwave heating, as it was found that microwave heating reduced the moisture content in the CPO and this should prolong the shelf life of the product. The results in the previous section indicated that the optimum conditions for the ohmic pretreatment were 100°C for 8 min (depicted as "O8") and 800 W for 3 min for the microwave process ("M3"). From the preliminary results, two combined pretreatment conditions were designed as:

1) "O2-M2.25" = ohmic heating at 100°C for 2 min (25% of 8 min) followed by microwave heating at 800 W for 2.25 min (75% of 3 min) and

2) "O4-M1.5" = ohmic heating at 100°C for 4 min (50% of 8 min) followed by microwave heating at 800 W for 1. 5 min (50% of 3 min).

Table 3 summarizes the effects of the pretreatment method on the hardness of oil palm fruits, yield and qualities of the extracted CPO. The average hardness values of the sample pretreated using the processes O2-M2.25 and O4-M1.5 were 11.22±3.48 N and 9.38±2.19 N while the yields increased to 47.26% w/w and 47.22% w/w, respectively. From the SEM images, the outer shell of the oil palm fruits pretreated using the combined method looked drier than that of the ohmic-pretreated samples (data not shown). It was also found that the moisture contents in the CPO extracted from the sample pretreated by processes O8, M3, O2-M2.25 and O4-M1.5 were 0.24±0.02 % w/w, 0.21±0.05 % w/w, 0.18±0.05 % w/w and 0.20±0.01% w/w, respectively. The ability of the microwave heating to remove excess water from the sample was expected because it is a dry process. However, it was interesting that the moisture content of the CPO extracted from the samples pretreated using the combined methods was significantly lower than that pretreated using the microwave process only. In the combined process, the sample was initially treated using ohmic heating, which is a wet process, resulting in the formation of a number of pores in the shell of the oil palm fruit as confirmed by the SEM images in Fig. 2. A small amount of water could diffuse into the oil palm fruits through these pores which increased the moisture content of the sample. When the samples were further heated during the microwave process, the microwaves generated a rapid heating rate due to the dipolar nature of the water in these pores, resulting in a higher evaporation rate of the water. A relatively high yield of about 47% w/w was also obtained when the samples were pretreated by either process O2-M2.25 or O4-M1.5.

The combined process improved not only the yield but also the CPO quality. The FFA content was substantially reduced when the samples were pretreated using the new combined method. When the samples were treated using the process O2-M2.25, the FFA content reached the minimum value of 1.54% w/w. The reduction of the

Table 3 Effects of process on hardness of oil palm fruits, yield and quality of the crude palm oil

Process*	Hardness (N)	Yield (%w/w)	FFA (%w/w)	PV ($meqO_2/kg$)	β-carotene content (ppm)
O8	6.18 ± 0.43^{a}	46.30 ± 1.20^{ab}	1.86 ± 0.07^{b}	1.47 ± 0.06^{b}	459.5 ± 26.4^{a}
M3	8.46 ± 1.26^{b}	44.52 ± 1.43^{a}	1.74 ± 0.07^{b}	1.40 ± 0.36^{ab}	414.7 ± 20.8^{a}
O2-M2.25	11.22 ± 3.48^{b}	47.26 ± 1.05^{b}	1.54 ± 0.06^{a}	1.30 ± 0.10^{a}	438.3 ± 10.8^{a}
O4-M1.5	9.38 ± 3.79^{b}	47.22 ± 0.57^{b}	1.69 ± 0.11^{ab}	1.37 ± 0.51^{a}	471.0 ± 55.3^{a}

O = ohmic heating at 100°C and M = microwave heating at 800 W.

* = a number after a letter in the process column is the heating time. For example, O2-M2.25 = ohmic heating at 100°C for 2 min followed by microwave heating at 800 W for 2.25 min.

Mean (± SD) values with different lowercase superscripts within each column denote significant ($p < 0.05$) differences between groups.

FFA content could have been due to the higher heating rate when the sample contained a small amount of water during microwave heating. Furthermore, the PV of these samples was the lowest (1.30±0.10 meqO_2/kg). The palm oil industry generally requires the maximum FFA content and the PV value to be not higher than 5% w/w and 10 meqO_2/kg, respectively (Office of Industrial Product Standards of Thailand, 1978). The potential of the proposed combined process for crude palm oil production is highlighted by its ability to reduce the maximum FFA content and PV of the CPO by 69% and 87%, respectively.

Process time and energy consumption

Evaluation of the process time and energy consumption is important since these parameters directly affect the production cost. Fig. 5 shows the sample temperature profile and the electric current supplied to the sample during ohmic pretreatment at 160 V for 8 min. The energy required to preheat water in the come-up period of approximately 120 s was also included in the energy consumption calculation. At 120 s, the oil palm fruits were placed into the preheated water and this resulted in a decrease in the water temperature. When the sample was heated to 100.5°C, the temperature sensor cut off the electric power and subsequently, the water temperature slowly decreased. The power supply was reconnected when the water temperature dropped to 99.5°C. As presented in Table 4, the energy consumption of the ohmic pretreatment process was only 43% of the energy used by the microwave heating. In microwave heating, the microwaves are generated by a magnetron and randomly transmitted through the waveguide into the heating room. Though some of the microwave's energy can be absorbed by the foodstuff inside the heating room, a portion of energy is normally lost.

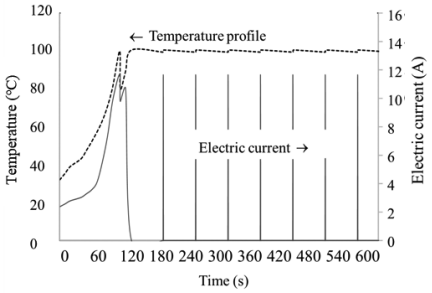

Fig. 5 Temperature profile and electric current passing through the sample during ohmic pretreatment at 160 V and 100°C for 8 min

Table 4 Energy consumption by pretreatment process, where values are means ± SD

Pretreatment process*	Energy consumption (kW-h/$kg_{palm\ oil}$)	Heating time (min)	Operation cost** (USD/$kg_{palm\ oil}$)
O8	0.20 ± 0.01	8	0.093
M3	0.47 ± 0.02	3	0.100
O2-M2.25	0.38 ± 0.05	4.45	0.097
O4-M1.5	0.32 ± 0.01	5.5	0.097

* = see footnotes in Table 3 for details of the numbers and letters in the pretreatment process column.

** = operation cost includes only energy and labor costs. Calculation based on energy cost of USD 0.167 /kW-h and a labor cost of USD 11 /man-day.

The current research reconfirmed the energy efficiency of the ohmic heating process compared to other methods and was in good agreement with Sakr and Liu (2014). In the current research, the ohmic pretreatment required water as the electrical path between the electrodes and the fruit sample. Because the mass ratio between the oil palm fruits and water was 1:2 and the temperature profiles of the water and the oil palm fruits were nearly the same, it was estimated that not less than two-thirds of the total energy used in the ohmic pretreatment was supplied to water. Though the results showed that the ohmic pretreatment required less energy than microwave heating and the traditional heating, it is still possible to improve the energy efficiency of the process by either minimizing the water used in the process or using a heat exchanger that will enable the reuse of the energy in the spent hot water. However, good water treatment management may be required to control the operational cost and the environmental impact.

Though the microwave process consumed more energy than the ohmic process, the production time of the process was 50% shorter than the ohmic process. Due to the fact that the production time is also another factor that affects the production cost, the new combined method seemed to be a compromise solution between optimizing the total production time or the energy efficiency of the process, as it reduced the production time to 5 min and saved about 20% to 30% of the energy compared to the microwave process. It should be noted here that the operation cost shown in Table 4 was estimated from the assumption that the energy cost was THB 5 /kw-h and the labor cost was THB 330 /day (based on Thailand minimum wage) or THB 0.69/min, and that one man could control three machine sets. For example, process "O8" required an energy cost = 0.20×5 = THB 1.0 /$kg_{palm\ oil}$ and a labor cost of 8×0.69 / 3 = THB 1.8 /$kg_{palm\ oil}$. Therefore, the total operation cost (including only the energy and labor costs) was approximately THB 2.8 /$kg_{palm\ oil}$ (or USD 0.093 /$kg_{palm\ oil}$). However, this was an estimate and the number could be varied if the energy cost, labor cost or production capacity of the machine were different. For example, for an automatic system, the labor cost might be much lower and the operation cost required to run an ohmic heating process would be much cheaper.

Quality of crude palm oil during storage

Lastly, the quality of the CPO samples extracted from O8, M3, O2-M2.25 and O4-M1.5 were analyzed after the samples had been kept in a dark room at 25°C for a maximum of 8 wk. Fig. 6 shows the changes in the CPO qualities during storage. The storage time significantly affected the quality of the CPO. At the 8th week of storage, all samples still contained less than 5% w/w FFA content, indicating that all the methods that were used to pretreat the oil palm fruits effectively controlled the FFA in the CPO. The FFA content of each sample increased with the storage time. The FFA contents of all ohmic-treated samples were not much different from the microwaved samples but were significantly higher than the sample in the O2-M2.25 treatment. At the 8th week of storage, the average

FFA content of the O2-M2.25-treated sample was only 2.86% w/w. Similarly, the PV strongly depended on the storage time. In the last week, the PV of only the O2-M2.25-treated sample was lower than the critical limit of 10 meqO_2/kg. It was also found that the *β*-carotene content of the CPO strongly depended on the storage time. All microwaved samples contained the lowest *β*-carotene content, regardless of the storage time. This could have been due to microwave heating being a dry process. The results agreed with Cardoso et al. (2014) who investigated the effects of dry and wet heat processes on the antioxidant profile of sorghum and reported that dry heat processes such as microwave heating and hot-air drying severely decreased the content and retention of *β*-carotene in the sample while the wet process did not. This would explain the higher *β*-carotene content in the CPO samples treated using O8, O2-M2.25 and O4-M1.5 compared to the microwaved sample.

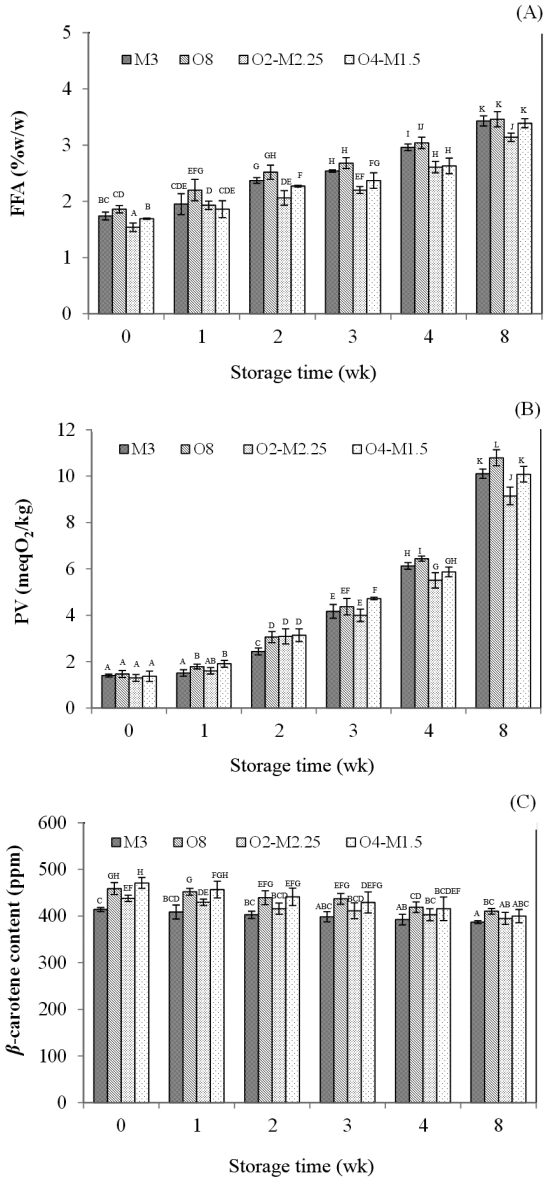

Fig. 6 Effect of storage time on crude palm oil quality: (A) free fatty acid (FFA) content, (B) peroxide value (PV), (C) *β*-carotene content, where footnotes in Table 3 explain the letters and numbers in the legend entries, w/w = weight per weight; meq O2 = milliequivalent of oxygen; ppm = parts per million and error bar = ± SD. Different superscripts above histograms denote significant ($p < 0.05$) different.

In conclusion, this study used a new, two-step method involving ohmic heating combined with microwave heating to pretreat fresh 'Tenera' oil palm fruits. The process increased the extraction yield by approximately 5% compared to the processes using microwave heating. Furthermore, the shelf life was successfully extended due to the low FFA and moisture contents in the CPO. The results confirmed that it was possible to use the two-step pretreatment process of ohmic heating combined with microwave heating to improve the CPO quality and stability. Large-scale and continuous-operating ohmic-microwave equipment should be designed, and the total capital cost should be evaluated for scale-up production of crude palm oil to implement the combined process in the palm oil industry in the future.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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