

Article

Pretreatment of Palm Fruit by Using a Conveyor Belt Microwave Prototype

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Abstract. This paper presents a microwave drying prototype, which is a conveyor belt design for oil palm pretreatment. The prototype consists of four 800 W magnetrons launching electromagnetic energy to the rectangular waveguide cavity. Palm fruit was fed in the cavity by the conveyor belt and pretreated in the cavity. The cavity size was designed optimally to ensure that temperature distribution in the palm fruit is uniform. Another conveyor belt is applied to the cavity output to feed out the pretreated fruit. Two corrugated waveguide filters were installed at the conveyor belt ends to suppress the microwave leakage. Three hundred sixty palm fruit were pretreated to prove the prototype concept. From the experiment results, the prototype heated palm fruit to the temperature required for inhibiting lipase enzyme within 120 seconds. It is found that free fatty acids in the treated palm fruit was well below 2% even 1 week storage.

Keywords: Pretreatment, microwave drying, oil palm, free fatty acids.

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1. Introduction

Oil palms, *Elasis quineensis* Jacq., are the crop with highest oil yield among the known oil plants [1, 2]. Products from these palms include crude palm oil (CPO), and crude palm kernel oil (CPKO) obtained from the mesocarp and kernel layers of palm fruit. Both CPO and CPKO are used by, for example, food industries, consumers, and energy sector.

There is a need for pretreating oil palm before extracting CPO from palm bunch and fruit. Currently, there are two popular processes, hot steam heating and frying. This pretreatment process is required to inhibit the hydrolysis of free fatty acids (FFA) inherent in the palm fruit [3, 4]. The FFA content is the key indicator of the CPO grade for producing vegetable oil. According to the commercial standard oil quality specifications, the FFA content of CPO should be well below 5% [4-6]. The formation of FFA in CPO can be considerably reduced by deactivating the lipase enzyme, and this is accomplished by heating the palm fruit to the specific temperature.

Many prior studies support microwave heating as rapid, uniformly, and environmentally friendly in comparison to convection heating, which is less energy efficient. Microwave energy generating from a high power microwave source penetrates heating objects and subsequently vibrates polar molecules in the objects. Friction around the vibrated molecules creates loss. Consequently, this dissipates microwave energy and heat objects [7]. There are several proposed works using microwave technique [3-5, 8-11]. Several designs were based on a household microwave oven which was not a suitable solution for palm pretreatment. When applying it to the problem, poor uniformity of electromagnetic (EM) field and temperature distribution in the palm fruit were obtained [4, 7, 12]. Moreover, pretreatment process using a household microwave oven is not continuous since it lacks a mechanism to automatically feed palm fruit through the cavity [13-15].

Part of the solution is to have continuous-belt feeding of the palm fruit through the cavity. A design concept for this was proposed, and the EM field and temperature distribution were simulated using the finite-element method [16]. Based on this design, the prototype implementation and its experiment results are first reported herein.

2. Design

EM field distribution in a microwave cavity, in which heating material contains, depends on the cavity dimensions and dielectric properties of the material. It is necessary to obtain a proper design for the cavity to provide a spatially uniform field distribution, which subsequently leads to spatially uniform heating in the heating material [7, 9]. A multi-mode rectangle cavity was designed and built. Both cavity ends are connected with

two conveyor belts. The cavity has 0.41 m width, 0.18 m height and 0.61 m length. The capacity of the cavity can pretreat palm fruit at the rate of 60 kg per hour. The target internal temperature of the fruit was around 70 °C, which would ensure inhibition of the lipase enzyme in the palm fruit and keep the FFA content of palm oil at very low level. This leads to determine the motor speed for controlling the conveyor belt at 30 cm/minute. Four 800 W magnetrons lie along the cavity length. Microwave power from these 2.45 GHz magnetrons is combined to obtain 3.20 kW radiated power. Four magnetrons are arranged in a parallel position to achieve the maximum combining and obtain spatially uniform heat distribution. The design was verified with simulation results performed using COMSOL™ Multiphysics software. To ensure the uniform heat distribution, the position non-orthogonal arrangement of magnetrons as shown in Fig. 1 was investigated. EM field along the x-axis in the cavity was analyzed by simulation. The electric field (E-field) distribution and mode generation were investigated.

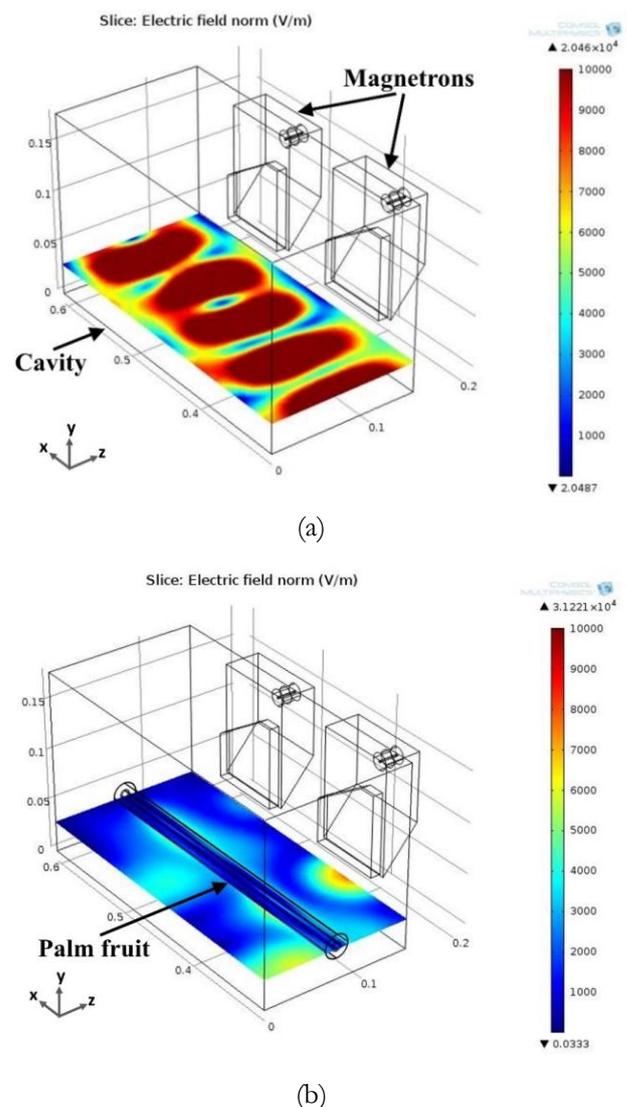


Fig. 1. E-field pattern (V/m) in the cavity half; (a) No-palm fruit scenario and (b) With-palm fruit scenario.

Table 1. $\tilde{\epsilon}(T)$ at 2.45 GHz of three fruit layers.

Layer	Dielectric constant
Kernel	$-1.560 \times 10^{-7} T^5 + 2.969 \times 10^{-5} T^4 - 1.975 \times 10^{-3} T^3 + 5.809 \times 10^{-2} T^2 - 0.720 T + 5.937$
Mesocarp	$1.302 \times 10^{-7} T^5 - 2.658 \times 10^{-5} T^4 + 2.068 \times 10^{-3} T^3 - 7.435 \times 10^{-2} T^2 + 1.222 T + 1.947$
Shell	$4.396 \times 10^{-8} T^5 - 4.614 \times 10^{-6} T^4 - 3.924 \times 10^{-5} T^3 + 1.620 \times 10^{-2} T^2 - 0.415 T + 4.060$
Layer	Dielectric loss factor
Kernel	$-6.288 \times 10^{-8} T^5 + 1.135 \times 10^{-5} T^4 - 7.335 \times 10^{-4} T^3 + 2.111 \times 10^{-2} T^2 - 0.256 T + 1.286$
Mesocarp	$3.750 \times 10^{-8} T^5 - 8.102 \times 10^{-6} T^4 + 6.605 \times 10^{-4} T^3 - 2.451 \times 10^{-2} T^2 + 0.408 T + 0.241$
Shell	$-3.276 \times 10^{-10} T^6 + 7.499 \times 10^{-8} T^5 - 6.352 \times 10^{-6} T^4 + 2.418 \times 10^{-4} T^3 - 3.966 \times 10^{-3} T^2 + 2.652 \times 10^{-2} T - 5.087 \times 10^{-2}$

T=Temperature (°C)

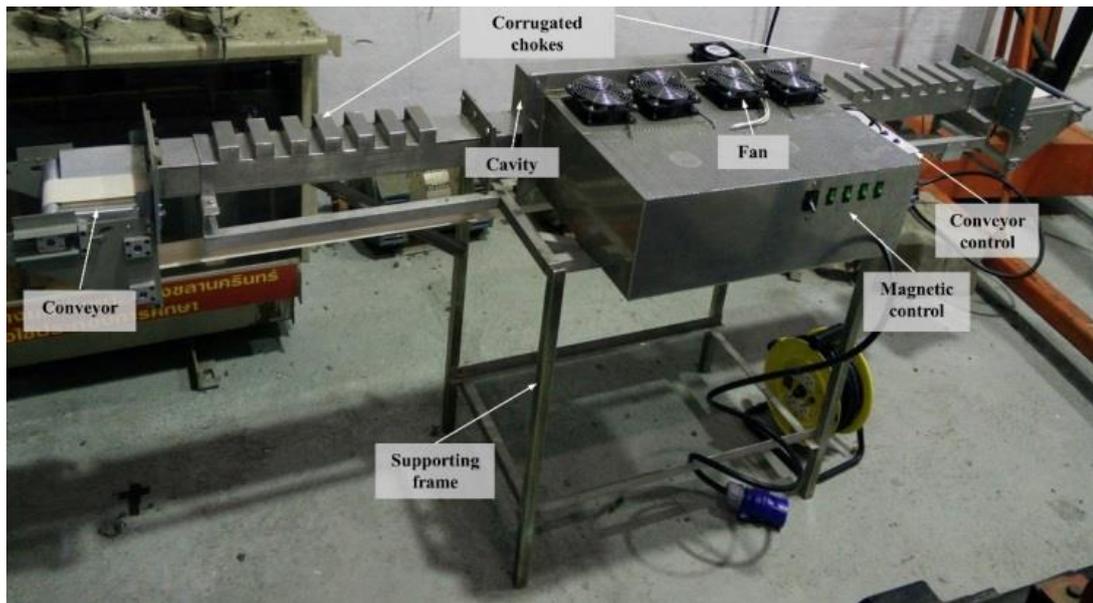


Fig. 2. Photograph of the prototype system.

A three-dimensional Finite Element Method (FEM) was performed using COMSOL™ Multiphysics software. High power microwave with TE₁₀ mode was launched from each magnetron via the waveguide. Since the cavity is symmetry around $x = 0$ plane, symmetric field distribution is guaranteed. Hence the simulation was performed in the cavity half only. This reduced the computation task considerably. Figure 1(a) show simulation results of the E-field (\vec{E}) in the cavity half. The field distribution exhibits TE₉₀₁ mode. This is observed from the pattern on the xz-plane which shows four full and a half wave along the x-axis and one full wave along the z-axis. The mode of propagation was generated by the reflections from the walls of cavity constructively reinforce each other to produce a standing wave [17]. The maximum in the cavity was 20.46 kV/m while the minimum was close to zero.

To provide good temperature distribution in palm fruit in the cavity, a continuous-belt design is proposed. To achieve this, a three-layer dielectric model of palm fruit was developed. The model includes both temperature-dependence dielectric ($\tilde{\epsilon}(T)$) and thermal properties of each fruit layer [7]. In practice, several palm fruit is fed continuously in the cavity by the moving belt. This can be visualized as a line of palm fruit in the cavity

along the x-axis. In such scenario, we use a cylindrical dielectric model to represent several palm fruit moving in the cavity. The dielectric cylinder as shown in Fig. 1(b) has its length equal to the cavity length where its cross-section is equal to the cross section of palm fruit. The model consists of three dielectric layers of palm fruit [16]. The $\tilde{\epsilon}(T)$ at 2.45 GHz of all three palm fruit are formed with polynomial functions shown in Table 1. The thermal properties of the microwave application for heating the palm fruit, the three following parameters, thermal conductivity (k), density (ρ), and specific heat capacity (C_p), were included in the model [18, 7].

Figure 1(b) shows the \vec{E} distribution when the cylinder model is applied in the cavity. \vec{E} at the air and palm fruit exocarp interface is reduced as compared with no fruit scenario in Fig. 1(a). The magnitude of \vec{E} intensity ranges from 1 to 4 kV/m, depending on the dielectric property of the palm fruit material. The field variation varies with space which is related to envelope of the standing wave in the cavity. When fruit is exposed to \vec{E} , energy of the field will be absorbed and subsequently converted to heat. Hence the increase of temperature in the palm fruit results from the increase of absorbed power with elapsed time [10]. To investigate

this, we observed the temperature change in the fruit with the heat-electromagnetic conversion rule at 60, 120, 180 and 240 seconds. The temperature results were calculated with the FEM using COMSOL™ Multiphysics software. The initial temperature of palm fruit was assumed at 30.0 °C. Heating time of 180 and 240 seconds may burn the palm fruit. At 60 seconds the temperature produced is not high enough. For a temperature around 70 °C, in our case 69 °C, the corresponding heating time was 120 seconds, and this is appropriate to deactivate the lipase enzyme that produces FFA. The information obtained can be used to configure a motor speed for controlling the continuous belt.

Figure 2 is the photograph of the prototype. A conveyor belt feeds the palm fruit continuously through the cavity. The conveyor is driven with a 4.2V/2.9A stepping motor and a stress roller. The belt speed is accurately controlled with a control circuit. A high AC voltage at 2.2 kV obtained from a high-voltage transformer (1:10 ratio) drives the four magnetrons. The system includes a protection circuit for safety. High-power electric devices and four electric fans were chosen. During the pretreatment, microwave leakage via the cavity port is minimized. According to the standard issued by International Commission on Non-Ionizing Radiation Protection (ICNIRP), the specific absorption rate (SAR) must be kept below 10 mW/cm² at 2.45 GHz [19-21]. Two corrugated waveguide filters installing at the input and output ports of the cavity were applied to reduce the leakage to meet the ICNIRP requirement

2.1. Moisture Ratio

The transport of moisture in the palm fruit is assumed to follow Fick's second law, as follows [22].

$$\frac{\partial M}{\partial t} = (\nabla^2 D_{eff} M) \quad (1),$$

where D_{eff} is the effective moisture diffusivity of palm fruit (m²s⁻¹) and M is the moisture content at time. If we assume that the fruit is spherical, the moisture ratio, MR , can be computed from [23, 24; 7, 10],

$$MR = \frac{(M - M_e)}{(M_0 - M_e)} = \frac{6}{\pi^2} \sum_{n=1}^{\infty} e^{\left[-n^2 \frac{\pi^2 D_{eff} t}{r^2}\right]} \quad (2),$$

where M_0 is the initial moisture content, M_e is the equilibrium moisture content, r is the palm fruit radius, and t is the heating time. Equation (2) can be simplified further by neglecting the higher order terms [25, 26] and assuming M_e to be zero [26-28]. Hence

$$MR \cong \frac{6}{\pi^2} e^{\left[-n^2 \frac{\pi^2 D_{eff} t}{r^2}\right]} \quad (3).$$

Taking the natural logarithm to both sides of Eq. (3), one obtains

$$\ln(MR) = \ln\left(6\pi^{-2}\right) - \frac{\pi^2 D_{eff}}{r^2} t \quad (4)$$

Equation (4) shows that a plot of MR (in natural log scale) versus t should be linear. Let m be the slope of this graph, then D_{eff} is given by

$$m = -\frac{\pi^2 D_{eff}}{r^2} \quad (5).$$

2.2. Activation Energy

Diffusivity of moisture content in the solid phase, normally defined as D_{eff} , depends on activation energy; E_a . The temperature distribution in heating palm fruit influences the drying process more than the initial moisture content of the palm fruit [26-29]. From the Arrhenius equation, E_a is calculated by

$$D_{eff} = D_0 e^{\left[\frac{-E_a}{RT}\right]} \quad (6),$$

where D_0 is the Arrhenius factor (m²s⁻¹), E_a is the activation energy (kJ (kg mol)⁻¹) and R is the gas law constant (kJ (mol)⁻¹). Equation (6) can be rearranged in a linear form by applying the logarithmic function as shown:

$$\ln(D_{eff}) = \ln(D_0) - \frac{E_a}{RT} \quad (7).$$

It is shown that the function of $\ln(D_{eff})$ and $\frac{1}{T}$ defined in Eq. (7) are linearly related with a straight slope of $-\frac{E_a}{R}$. E_a and D_0 were simultaneously determined by linear regression which fits with Eq. (7). These two parameters were obtained for 3.2 kW microwave power.

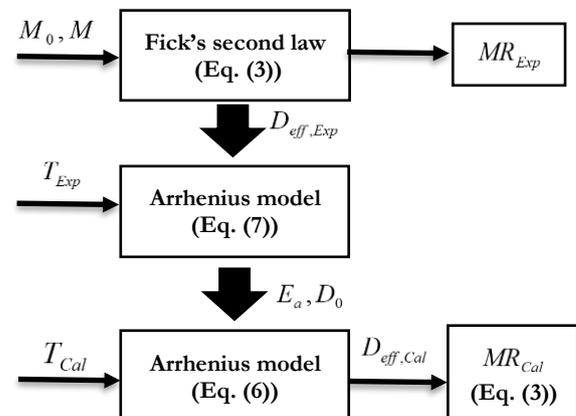


Fig. 3. Flow diagram for drying kinetics.

Figure 3 shows a flow diagram for the efficiency computations in this paper. The moisture ratio is first computed from Eq. (3), where D_{eff} of the palm fruit is determined from Eq. (3). Finally, D_0 and E_a parameters are evaluated from the measured temperature and D_{eff} using Eq. (7).

3. Materials and Methods

All palm fruit samples were collected locally in Songkhla province, Thailand. Several fresh palm fruit bunches were collected from thirteen-year-old trees. Specifically, only ripe palm fruit bunches were selected. Three hundred sixty fruit samples were collected from several bunches and were pretreated with the prototype within 24 hours. Before the heating, the weight of each fruit was measured with a digital balance (0.1 gram uncertainty) and the diameters were measured with a digital caliper (Mitutoyo, 150 mm/6" Absolute Digital Digimatic Vernier Caliper, Japan) with an accuracy of 0.01 mm. The lengths, widths and weights of the samples were 40.32 ± 3.60 mm, 30.16 ± 2.24 mm, and 15.71 ± 2.90 g, respectively. After the pretreatment with the prototype, the weights of the palm fruit were immediately measured. The recorded weights after and before pretreatment are applied to computed the MR . It is noted that the initial moisture content M_0 of the samples ranges from 29.40 to 29.80% wet basis, with 29.60 mean and 0.20 standard deviation.

We observed the temperature change in the palm fruit at 120, 180 and 240 seconds. The 60 second pretreatment time was omitted since, according to the simulation results, it gives a final temperature far below 70 °C which is insufficient to inhibit the lipase enzyme. The temperatures in the palm fruit at different pretreatment durations were recorded and compared with those obtained from the simulation results. A FLIR i3 thermal camera with an infrared sensor (accurate up to $\pm 2\%$ of its reading), was used to measure the average temperature in the mesocarp layer.

The FFA contents in CPO extracted from treated and untreated palm fruit were measured. Each treatment group was stored separately in a moisture-controlled cabinet for up to 7 days. On days 1, 3, 5, and 7, 192 palm fruits were sampled from each group to extract CPO, and the FFA contents of CPO samples were measured. All palm fruit samples were cut in small pieces and then pressed with a hydraulic presser to squeeze the CPO. After that, the standard FFA measurement was performed by Specialized R&D Center for Alternative Energy from Palm Oil and Oil Crops, Prince of Songkla University. It was determined by using the titration method as written in the MPOB Test Method with some modification [30, 31]. It used neutralized 2-propanol in amount of 50 ml to neutralize 0.5-2.0 g of palm oil sample. After regulating the temperature to 40°C, the sample was titrated against standard sodium hydroxide

(0.1 mol) using phenolphthalein 1% as indicator to first permanent pink.

4. Results and Discussion

4.1. Temperature Distribution

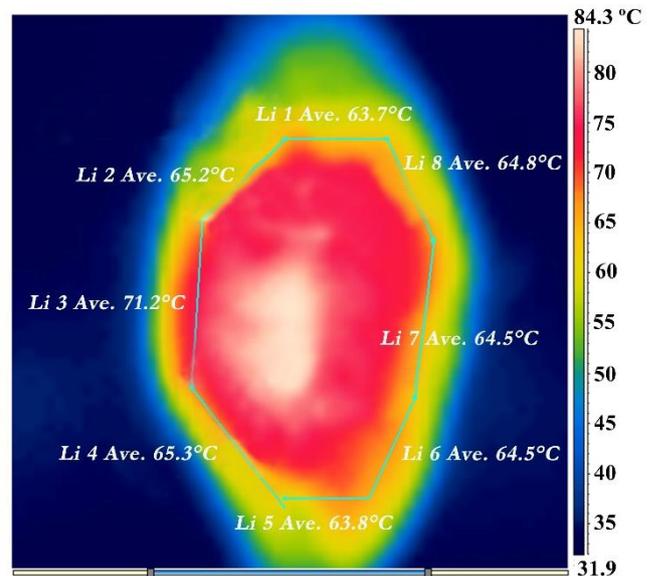


Fig. 4. Temperature distribution in a palm fruit sample.

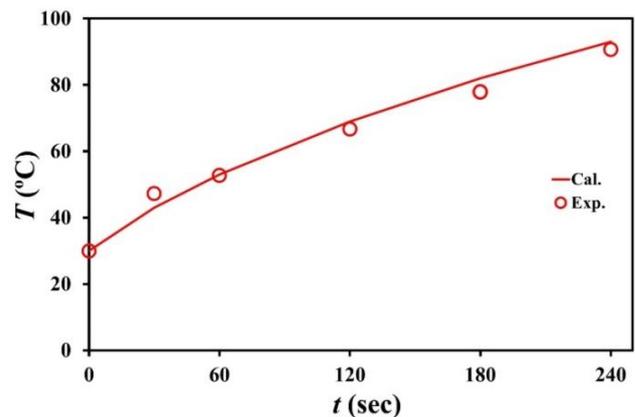


Fig. 5. Comparison of measured and calculated temperatures in the mesocarp layer.

Figure 4 shows the thermal image of one of the test samples. The blue background represents the surrounding environment and the color change from green to pink shows that the inner part had a higher temperature than the surface. Figure 5 shows the mean temperature profile in the mesocarp layer of all palm fruit samples. The calculated and experimented temperature values are compared for 3.2 kW power (four 800 Watt magnetrons) at 30, 60, 120, 180, and 240 seconds. The temperature in the mesocarp layer from computations at 30, 60, 120, 180, and 240 sec are 43, 53, 69, 82, and 93 °C, respectively. While the experimented average temperature means in the mesocarp layer at 30, 60, 120, 180 and 240 sec are 47.29 ± 0.32 °C, 52.75 ± 2.25 °C, 66.73 ± 2.21 °C, and 90.70 ± 5.79 °C, respectively. The

initial moisture content of the palm fruit samples was high, and the electromagnetic waves penetrated the palm fruit and made the water molecules rotate with the wave polarity. This created thermal energy and the temperature of palm fruit increased rapidly. The water molecules that absorbed energy moved towards the palm fruit surface so that moisture content was transferred from core to surface, following Fick's second law of diffusion [22-24].

As shown in Fig. 5, the increase rate of temperature slowly decays with time because the water was evaporated from the palm fruit surface. The target temperature around 70 °C is reached when the palm fruit was pretreated for 120 seconds. The simulation results are in good agreement with experiments with 0.996 correlation coefficient, which confirms the accuracy of temperature prediction by the simulation under the microwave irradiation.

4.2. Moisture Ratio

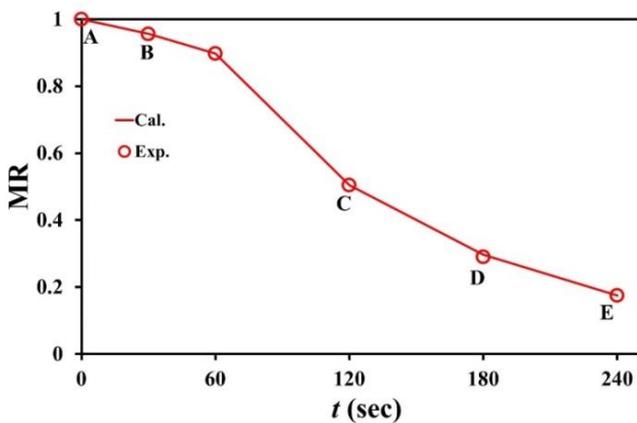


Fig. 6. Moisture ratio.

The average *MR* means from computations and experiments at 30, 60, 120, 180, and 240 sec, at 3.2 kW power are shown in Fig. 6. The computation results agree very well with the experiments, giving $R^2 > 0.998$, $RMSE < 2.628 \times 10^{-3}$ and $\chi^2 < 8.285 \times 10^{-6}$. As shown in Fig. 6, a very low *MR* is obtained in the A-B interval due to the initial stage of heating. In the B-C interval, a large amount of water has absorbed microwave energy and is evaporated, so that *MR* drops rapidly. At this stage, a large amount of water has diffused to the exocarp layer. At point C, the heating process is called the *critical moisture content*. Water around surface of sample is unstable distribution. When the heating process is continued, it reaches to the C-D interval. At this stage, the moisture evaporated rate is in the *first falling rate* state. The transfer rate of moisture from the endocarp layer to the exocarp layer becomes the rate-limiting step that slows down the evaporation at the exocarp layer, and the sample surface becomes drier. At point D, no water remains in the exocarp. The D-E interval is in the *second falling rate* stage, in which the rate of evaporation further drops. During this stage, water continuously evaporates until its quantity reaches equilibrium at point E in Fig. 6.

With full-power delivering (3.2 kW) for 240 seconds, the moisture content in fruit samples was, on average, reduced from 29.86% (w.b.) to 5.23% (w.b.). The upscale of the microwave pretreatment system for the palm fruit has evaporated moisture from the palm fruit, resulting in lower cavity temperature. To upscale, system solves the problem of installing a hot-air heater to expel the moisture content from the cavity [32, 33].

4.3. FFA

The FFA content of CPO for the trading purpose must not exceed 5% [4-6]. When the palm bunch is cut during palm fruit harvesting, enzymes start to catalase and breaking down the triglycerides into FFA and partial glycerides. The increasing FFA deteriorates the CPO. Thus, it is important to keep the FFA content as low as possible.

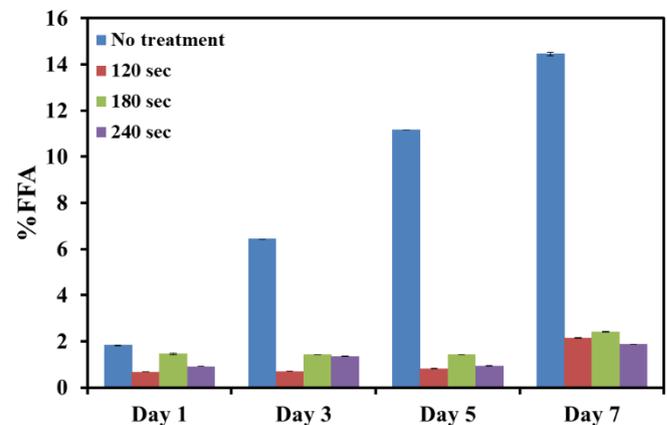


Fig. 7 Time profiles of FFA content (%) in CPO with several heat treatments in the microwave pretreatment system.

Figure 7 shows the performance of a microwave pretreatment system to deactivate the lipase enzyme. The FFA content in CPO extracted from treated and untreated control palm fruit were measured. The actual treatments had three alternative heating times: 120, 180, and 240 sec. It is shown in Fig. 7 that the CPO extracts from the heated samples had much lower FFA contents than the controls. The FFA in control exceeded 15%, which is no longer acceptable. On the other hand, with actual treatments the FFA contents in CPO stayed well below 5%, remaining acceptable; they ranged from 0.683 ± 0.001 to $2.409 \pm 0.008\%$. These cases would satisfy the CPO quality standards after 7 days of storage. The correlation coefficient between the 7-day storage period and the FFA content in CPO from treated at 120, 180, and 240 sec are 0.824, 0.760, and 0.712, respectively.

We achieved to extend the shelf life of the CPO extracts with the microwave-based pretreatment system. We found from the experiment that the heated samples could be kept for at least seven days with the FFA contents remaining below 5%. At a pretreatment time of 120 seconds, we obtained 67 °C for the average

temperature in the palm fruit. This temperature is sufficient to deactivate the lipase enzyme that produces and slowly increases FFA. It is shown in Fig. 7 that the FFA is well below 2.00%, even one-week storage. Also, the physical colour of CPO remained reddish-brown, making the colour of oil product marketable. Meanwhile, the palm fruit texture was still soft so that the oil production at the subsequent stage can be readily done. On the other hands, the process caused burns of the palm fruits and changed the CPO into dark colour at a heating time of 180 and 240 seconds. Consequently, the optimum pretreatment duration is 120 seconds with the concerns of FFA level and physical properties of the CPO after 7-days storage as shown in Fig. 8.



Fig 8. CPO on heat treatments after 7 days of storage.

5. Conclusions

A prototype continuous-belt microwave pretreatment system for palm fruit has been designed, developed and experimentally demonstrated. The system had four 800W magnetrons operating at 2.45 GHz for heating palm fruit to 67 degrees Celsius within 120 seconds. The pretreated palm fruit could be stored for at least seven days while the FFA contents stayed well below 5%, the standard limit observed by the oil industry. We believe that this prototype is a possible solution for using in small-scale and medium-scale plants for palm oil production.

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References

- [1] S. Prasertsan and P. Prasertsan, "Biomass residues from palm oil mills in Thailand: An overview on quantity and potential usage," *Biomass and Bioenergy*, vol. 11, no. 5, pp. 387-395, May 1996.
- [2] S. Sumathi, S. P. Chai, and A. R. Mohamed, "Utilization of oil palm as a source of renewable energy in Malaysia," *Renewable and Sustainable Energy Reviews*, vol. 12, no. 9, pp. 2404-2421, 2008.
- [3] S. Khumhom, W. Ajharnand, and C. Tongsopa, "Study of application of belt type microwave oven in oil palm sterilization process," *Thai Society of Agricultural Engineering*, vol. 10, no. 1, pp. 36-41, 2009.
- [4] I. Umudee, M. Chongcheawchamnan, M. Kiatweerasakul, and C. Tongurai, "Sterilization of oil palm fresh fruit using microwave technique," *International Journal Chemical Engineering and Applications*, vol. 4, no. 3, pp. 111-395, Jun. 2009.
- [5] M. C. Chow and A. N. Ma, "Processing of fresh palm fruits using microwaves," *Journal of Microwave Power and Electromagnetic Energy*, vol. 40, no. 3, pp. 165-173, Feb. 2007.
- [6] A. Choto, C. Thongurai, N. Kladkaew, and M. Kiatweerasakul, "Sterilization of oil palm fruit using radio-frequency heating," *International Journal of Advances in Chemical Engineering and Biological Sciences*, vol. 1, no. 1, pp. 123-126, 2014.
- [7] K. Puangsuwan, M. Chongcheawchamnan, and C. Tongurai, "Effective moisture diffusivity, activation energy and dielectric model for palm fruit using a microwave heating," *Journal of Microwave Power and Electromagnetic Energy*, vol. 49, no. 2, pp. 100-111, May 2015.
- [8] N. Sukaribin and K. Khalid, "Effectiveness of sterilization of oil palm bunch using microwave technology," *Industrial Crops and Products*, vol. 30, no. 2, pp. 179-183, Sep. 2009.
- [9] I. Mohd Halim Shah, A. A. Mustafa Kamal, and M. Noor Azian, "A systems approach to mathematical modelling of sterilization process in palm oil mill," *European Journal of Scientific Research*, vol. 35, no. 4, pp. 583-592, 2009.
- [10] K. Puangsuwan, B. Pamornak, C. Tongurai, and M. Chongcheawchamnan, "Complex permittivity of fully ripe palm fruit and its application for microwave heating," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 21, no. 3, pp. 1415-1423, Jun. 2014.
- [11] S. F. Cheng, L. M. Nor, and C. H. Chuah, "Microwave pretreatment: A clean and dry method for palm oil production," *Industrial Crops and Products*, vol. 34, no. 1, pp. 967-971, Jul. 2011.
- [12] Y. Wang, Y. Li, S. Wang, L. Zhang, M. Gao, and J. Tang, "Review of dielectric drying of foods and agricultural products," *International Journal of Agricultural and Biological Engineering*, vol. 4, no. 1, pp. 1-19, Mar. 2011.
- [13] D. Boldor, T. H. Sanders, K. D. Swartzel, and B. E. Farkar, "A model for temperature and moisture distribution during continuous microwave drying," *Journal of Food Process Engineering*, vol. 28, no. 1, pp. 68-87, Apr. 2015.
- [14] D. Boldor, T. H. Sanders, K. R. Swartzel, and J. Simunovic, "Thermal profiles and moisture loss during continuous microwave drying of peanuts," *Peanut Science*, vol.32, no. 1, pp. 32-41, Jan. 2015.

- [15] L.P. Fennell and D. Boldor, "Continuous microwave drying of sweet sorghum bagasse biomass," *Biomass and Bioenergy*, vol. 70, no. 1, pp. 542-552, Nov. 2014.
- [16] K. Puangsuwan, C. Tongurai, and M. Chongcheawchamnan, "Design of microwave heating continuous belt system for palm fruit," in *Asia Pacific Microwave Conference (APMC)*, Nanjing, China, 2015, pp. 1-3.
- [17] C. A. Balanis, *Advanced Engineering Electromagnetics*, 2nd ed. New York, USA: John Wiley, 2012.
- [18] B. R. Becker and B. A. Fricke, "Food thermo physical property models," *International Communications in Heat and Mass Transfer*, vol. 26, no.5, pp. 627-636, 1999.
- [19] A. L. Von Koaghnnett and J. Dynni, "Doubly corrugated chokes for microwave heating systems," *Journal of Microwave Power*, vol. 8, no. 1, pp. 101-110, 1973.
- [20] Y. Pianroj, W. Jindarat, and P. Rattanadecho "A design of doubly corrugated filter for the continues belt microwave drying system," in *The 22nd Conference of Mechanical Engineering Network of Thailand*, Pathum Thani, Thailand, 2008, pp. 226-229.
- [21] P. Soto, V. E. Boria, J. M. Catalá-Civera, N. Chouaib, M. Guglielmi, and B. Gimeno, "Analysis, design, and experimental verification of microwave filters for safety issues in open-ended waveguide systems," *IEEE Transactions on Microwave Theory and Techniques*, vol.48, no. 11, pp. 2133-2140, Nov. 2000.
- [22] J. Crank, *The Mathematics of Diffusion*. Oxford: Clarendon Press, 1975.
- [23] Q. Liu and F. W. Bakker-Arkema, "Stochastic modeling of grain drying: Part 2. Model development," *Journal of Agricultural Engineering Research*, vol.66, no. 4, pp. 275-280, Apr. 1997.
- [24] W. Senadeera, B. R. Bhandari, G. Young and B. Wijesinghe, "Influence of shapes of selected vegetable materials on drying kinetics during fluidized bed drying," *Journal of Food Engineering*, vol. 58, no. 3, pp. 277-283, Jul. 2003.
- [25] B. Adu and L. Otten, "Diffusion characteristics of white beans during microwave drying," *Journal of Agricultural Engineering Research*, vol. 64, no. 1, pp. 61-69, 1996.
- [26] S. J. Babalis and V. G. Belessiotis, "Influence of the drying conditions on the drying constants and moisture diffusivity during the thin-layer drying of figs," *Journal of food Engineering*, vol. 65, no. 3, pp. 449-458, 2004.
- [27] S. Minaer, A. Motevali, G. Najafil, and S. R. M. Seyedi, "Influence of drying methods on activation energy, effective moisture diffusion and drying rate of pomegranate arils (*Punica Granatum*)," *Australian Journal of Crop Science*, vol. 6, no.4, pp. 584-591, 2011.
- [28] A. Motevali, A. Abbaszadeh, S. Minaei, M. H. Khoshtaghaza, and B. Ghobadian, "Effective moisture diffusivity, activation energy and energy consumption in thin-layer drying of jujube (*Zizyphus jujube mill*)," *Journal of Agricultural Science and Technology*, vol. 14, pp. 523-532, 2012.
- [29] A. Maskan, S. Kaya, and M. Maskan, "Hot air and sun drying of grape leather (pestil)," *Journal of Food Engineering*, vol. 54, no. 1, pp. 81-88, 2002.
- [30] Malaysian Palm Oil Board (MPOB), *MPOB Test Methods*. 2004.
- [31] *AOCS Official Method Ca 5a-40, Free Fatty Acids*, American Oil Chemists' Society, Boulder, Urbana, 2009.
- [32] W. Jindarat, P. Rattanadecho, S. Vongpradubchaia, and Y. Pianroj, "Analysis of energy consumption in drying process of non-hygroscopic porous packed bed using a combined multi-feed microwave-convective air and continuous belt system (CMCB)," *Drying Technology*, vol. 29, no. 8, pp. 926-938, 2011.
- [33] R. Prommas, P. Rattanadecho, and W. Jindarat, "Energy and exergy analyses in drying process of non-hygroscopic porous packed bed using a combined multi-feed microwave-convective air and continuous belt system (CMCB)," *International Communications in Heat and Mass Transfer*, vol. 39, pp. 242-250, 2012.



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