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Research article

# Production of Red Palm Oil and Red Palm Fats by Vacuum Frying Sterilization and Multi-step Fractionation

**Jeerapong Rakprasoot[1], Warangkana Temeeya[2], and Patcharin Raviyan[3*]**

[1] Division of Food Science and Technology, Faculty of Agro-Industry, Chiang Mai University, Chiang Mai, 50100. Thailand
[2] Division of Food Science and Technology, Faculty of Agro-Industry, Chiang Mai University, Chiang Mai, 50100. Thailand
[3] Division of Food Science and Technology, Faculty of Agro-Industry, Chiang Mai University, Chiang Mai, 50100. Thailand
* Correspondence: patraviyan@gmail.com

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**Abstract:** The question of the health impact of refining palm oil has driven the oil palm producers in Thailand toward developing wellness products that are in high demand in the future. Red palm oil, rich in carotenoids and vitamin E, catches attention. However, the production of red palm oil using the current steam sterilization method harms the environment and requires a high capital investment. In contrast, the cost-saving dry sterilization method delivers a low-quality product. The vacuum frying method was studied to develop an effective red palm oil processing method suitable for small and medium-size enterprises (SMEs). The production steps include vacuum frying sterilization, acid degumming, neutralization, and multi-step fractionation. The steam sterilization method was compared using the same arrangement step except for the sterilizing procedure. Sterilization by the vacuum fryer was controlled at 80 °C, -400 to -720 mmHg. Results showed that the optimal vacuum frying time was 90 min. The fractionation temperatures of the vacuum frying method were 34 °C, 27 °C and 17 °C, whereas those of the steam sterilized method were 34 °C, 25 °C and 15 °C. The quality of the red palm oils produced from both methods was within the edible oil standard. The vacuum frying method produced red palm oil with 0.17% free fatty acids, 6.70 meq.$O_2$/kg peroxide value, 620 mg/kg carotenoids, 835 mg/kg vitamin E, and 61.31% yield. The main advantage of the vacuum frying method's quality lies in improving yield and oil odor, which is a sensory characteristic that plays an important role in consumer acceptance of the product. The red palm fats obtained from the multi-step fractionation provided a wide range that is suitable for different applications. Therefore, vacuum frying could be considered a sustainable technology that is appropriate for SMEs.

**Keywords:** Vacuum frying sterilization; Multi-step Fractionation; Red palm oil; Red palm fat; Crude palm oil

## 1. Introduction

Red palm oil is a less refined palm oil containing several phytonutrients important for good health, such as carotenoids, vitamin E, sterols, phospholipids, glycolipids, and squalene [1]. The distinctive characteristic of red palm oil is its red color due to its high content of carotenoids [2]. Production of red palm oil consists of two major steps: crude palm oil preparation and fractionation [2]. Preparing crude palm oil for red palm oil production should not undergo bleaching and deodorizing processes that destroy phytonutrients but mainly involve bunch reception, fruit sterilization, and oil extraction [3]. The fractionation step, where the solid phase is separated from the liquid phase, controls the selectivity of crystallization and separation [4].

Fruit sterilization is an important step that inactivates the lipase enzyme to prevent the formation of free fatty acids [5]. This treatment also softens and loosens the palm fruit to facilitate fruit digestion and oil extraction. Steam sterilization, where the palm bunches are sterilized in a sterilizer using steam generated by a boiler, has been widely used in large-scale operations. This process achieves high productivity but requires high capital investments. It also discharges large amounts of wastewater. In addition, the extracted oil is likely to develop off-flavor and discoloration [6]. For small-scale operations in Thailand, dry sterilization has been widely used. This process involves heating palm fruit in a utensil fired by fiber or palm shells. After sterilization, the fruits are extracted through a process called pressing, which involves the application of mechanical pressure to the whole fruits without separating the palm kernel from the mesocarp. This process is cost-saving in terms of machinery and maintenance, but it is difficult to control the heating parameters of the process, which leads to low-quality crude palm oil. Besides, the obtained crude palm oil is likely to have a smoky odor and contain residual substances from the burnt fiber.

Since low-quality crude palm oil would deliver low-quality red palm oil, a new method for producing high-quality red palm oil, namely the vacuum frying method, was developed in this study to overcome the limitations of the steam and dry sterilization methods. The important steps in the vacuum frying method consist of vacuum frying sterilization, acid degumming, neutralization, and multi-step fractionation. The vacuum frying sterilization is a green process where palm fruits are fried under vacuum conditions to rapidly remove water from the palm fruits without wastewater discharge. By controlling the vacuum level, frying temperature, and length of frying time, vacuum frying sterilization is expected to preserve most phytonutrients and improve the odor quality of red palm oil [7]. Good-quality red palm oil is expected when combining vacuum frying sterilization with the post-treatment degumming process, neutralization, deodorization, and fractionation.

Three fractionation techniques have been used in the palm oil industry, including detergent fractionation, solvent fractionation, and dry fractionation. The detergent fractionation has high separation efficiency, but it is expensive and has been found to cause the products to become contaminated with the detergent. In solvent fractionation, it provides a high yield and purity of the product, but its production cost and capital investment are high. Dry fractionation is the simplest and cheapest approach. There is no effluent, no chemicals, and less losses. However, the viscosity of the fat could be the problem when a single fractionation is operated in bulk. Multi-step fractionation can overcome the viscosity problem [8].

The vacuum fryer used in this study was invented at the Chaipattana Foundation in Cha-am District, Phetchaburi Province, Thailand. Crude palm oil was used as a frying medium because it is a stable, cheap, and readily available oil. However, the frying medium crude palm oil contains existing carotenoids, which may affect the results of this study's extracted crude palm oil. Thus, the migrations of carotenoids and the frying medium crude palm oil were calculated to validate the study's data. The frying parameters for palm fruits were designed at a temperature of 80 °C and pressure of -400 to -720 mmHg, whereas a certain frying time has never been reported. The low temperature used would reduce the adverse effects on the oil quality. The operating pressure should be low enough to cause a significant decrease in the boiling point of water, allowing frying to be performed at low temperature. In this study, the lowest pressure that could be operated was -720 mmHg, which enabled the frying temperature to be 80 °C. However, there was an increase in pressure towards the evaporation of water during vacuum frying. The highest pressure was detected at -420 mmHg. Regardless of the frying pressure, the palm fruit experienced the desired temperature of 80 °C.

After frying, oil was extracted from the palm fruits with a single screw press, which is normally used by Thailand's small-scale palm oil industry. The important factor influencing the single screw press performance is the fruits' moisture content. The higher moisture content promoted plasticity decreased the degree of compression, and resulted in poor oil yield. In addition, moisture acted as a lubricant in the barrel; thus, higher moisture content contributed to inadequate friction during pressing. However, too low moisture in the fruit caused high oil sediment [9]. Our preliminary study found that 7% moisture was optimal in single screw-pressing of palm fruit.

Therefore, the current study aimed to determine the vacuum frying time that reduces the water content of the palm fruit to 7%. Meanwhile, the appearance of the fried palm fruits taken from different frying times was evaluated to ensure the quality of the end products. Though the exact frying time cannot be applied to fruits with different sizes and initial water contents, the finding on the effect of frying time would be of fundamental importance for researchers or producers who want to implement this method. At the multi-step fractionation, the fractionation temperatures were examined. The properties of the red palm oils and red palm fats were compared using vacuum frying sterilization and steam sterilization. The dry sterilization method was not included in this study because our preliminary experiment suggested that the smoky smell of the crude palm oil sterilized by this method is too strong and unacceptable by most panelists.

## 2. Materials and Methods

### 2.1 Materials

Fresh palm fruits were obtained as bunches or loose fruits from the field of the Chaipattana Foundation Project, Phetchaburi Province, Thailand. The fruit bunch consists of palm fruits embedded in spikelets growing on a bunch stem. Manual threshing was achieved by cutting the fruit spikelets from the bunch stem with an axe. Then, the fruits were separated from the spikelets by the slitting machine. The steam-sterilized crude palm oil was processed at 120-140 °C for 45 min and obtained from Srisuk Palm Co., Ltd., Prachuap Khiri Khan, Thailand. The refined palm oil is purchased from the local market. The chemicals used were either analytical or HPLC grade.

### 2.2 Methods

#### *2.2.1 Red palm oil production*

#### *2.2.1.1 Vacuum frying sterilization*

The vacuum fryer used in this experiment is located at the Chaipattana Foundation Project, Phetchaburi Province, Thailand. The major parts of the vacuum fryer are shown in Figure 1. Fresh palm fruits with a water content of 35.05 ± 4.49% were previously removed from the bunches, then a batch of 700 kg palm fruits was placed into the vacuum fryer filled with 400 kg crude palm oil. The palm fruits were vacuum fried at 80 °C and a pressure of -400 to -720 mmHg. The palm fruits were collected after vacuum-fried for 15 min and examined for water content, yield, and appearance. This experiment was repeated at 30, 45, and 60 minutes, frying until the water content of the fruits was about 7%. At each frying time, migration of the frying medium crude palm oil into the palm fruits was calculated to obtain the actual oil yield. The yield and appearance of the fruits identified the optimal vacuum frying time. After that, the palm fruits were vacuum fried under the optimal condition and extracted by the screw press at a rate of 120 kg fruits/hr. The extracted oil was kept at 25 °C in a dark brown glass container and analyzed for carotenoid content [10], free fatty acids [11], iodine value [11], peroxide value [11], phosphorus content [12], iron [12], copper [12], vitamin E content [13], melting point (DSC8000, Perkin Elmer, USA) and solid fat content (Pluse Nuclear Magnetic Resonance Spectrometers, Bruker, Germany). The GC method analyzed the free fatty acids with a capillary column and hydrogen flame ionization detector. The analyzing conditions were an inlet temperature of 225 °C, a split ratio of 200:1, a flow rate of 0.75 ml/min, and helium as carrier gas [11]. The carotenoid contents of the crude palm oil before and after use as the frying medium were analyzed and used to determine the actual carotenoid contents in the extracted oil. Similar tests were performed on the crude palm oil prepared by steam sterilization.

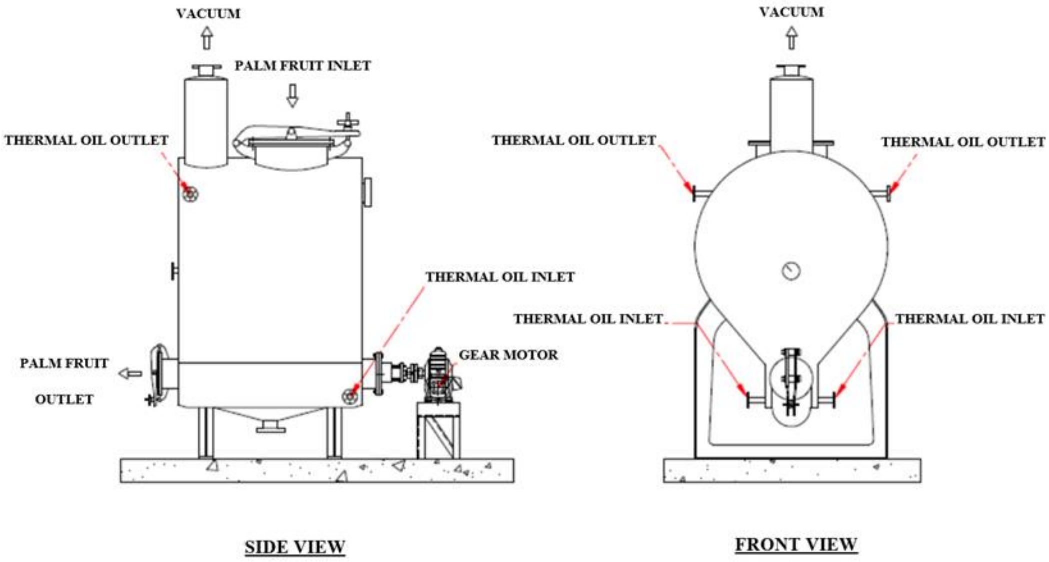


**Figure 1.** Components of the vacuum fryer (above) and appearance of the vacuum fryer (below)

### *2.2.1.2 Degumming and neutralization*

The crude palm oil samples obtained from the vacuum frying and steam sterilizations were degummed and neutralized using the procedures described by Rakprasoot et al. [14]. Briefly, two hundred grams of the sterilized oil sample were degummed at 90 °C with vigorous stirring for 20 min. A mixture of 0.06% phosphoric acid and 0.04% citric acid per oil weight was diluted 9 times with distilled water before mixing with the crude palm oil. The sedimented gum was separated from the oil by washing the oil with warm water at 60 °C. Then, the oil was evaporated at 80 °C under vacuum for 30 min to reduce the water content to less than 7%. The excess free fatty acids and phosphorus were removed by neutralization with 20% NaOH at 80 °C for 30 min. Soap and excess NaOH were washed with warm water at about 60 °C. The oil samples were vacuum-dried at 50 °C until the water content was less than 0.1%. The oil samples were analyzed for yield [10], carotenoid content [10], free fatty acids [11], phosphorus [12], iron [12], and copper [12].

### *2.2.1.3 Multi-step fractionation*

After degumming and neutralization, the multi-step fractionation was performed using the predetermined temperatures and the predetermined cooling rate (0.17 °C/min). The fractionation was operated in a 3,000 ml glass reactor (model JGR1L, Yuchem brand, China) equipped with a cooling system (model SDC-6, Drywell brand, China). The procedure started by adjusting the oil temperature to 60 °C and then reducing the oil temperature to 5 different levels starting from 35 °C. When the oil temperature reached each predetermined level, the temperature was maintained for 30 min. The sample was then vacuum-filtered to separate the red palm fats from the oil fraction. The major unit operations in red palm oil and fat processing are shown in Figure 2. The obtained red palm fats and the red palm oil were analyzed for fatty acids composition [12], yield [10], iodine value [11], free fatty acids [11], peroxide value [11], melting point (DSC, Perkin Elmer, USA), carotenoids content [10], vitamin E content [13] and solid fat content (Pulse Nuclear Magnetic Resonance Spectrometers, Bruker, Germany).

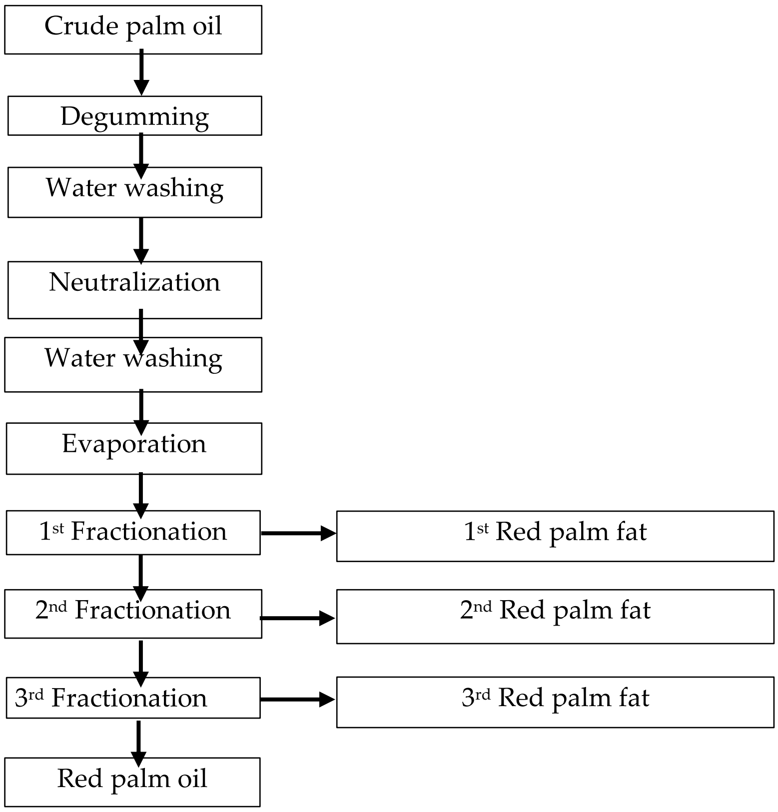


**Figure 2.** The major unit operations in red palm oil and red palm fats processing.

***2.2.2 Consumer acceptance test***

***2.2.2.1 The red palm oils***

The commercial refined palm oil (control) and the red palm oil derived from the vacuum frying and the steam sterilization methods were presented to the healthy, trained 50 panelists aged between 20-25 years. The test included evaluation of appearance, clearness, color, odor, and overall acceptability using the 9-point hedonic scale, ranging from "dislike extremely" =1 to "like extremely" =9 [15]. The experimental design was a randomized complete block design. The panelists were advised to clean the leftover previous aroma in their nasal cavity by sniffing roasted coffee beans between evaluations of each sample.

***2.2.2.2 The deep-fried potato sticks***

The experiment followed the procedure of Chompoo et al. [15] with minor modifications. The potato sticks were prepared and deep-fried in refined palm oil (control), and the red palm oils were derived from the vacuum frying and steam sterilization methods. Acceptances of the deep-fried potatoes or the French fries were evaluated using a 9-point hedonic scale with specific attributes, including appearance, odor, crispness, flavor, crispness aftertaste, and overall acceptability (N=50). The experiment was designed using a randomized complete block design.

#### *2.2.3 Statistical analysis*

All the determinations mentioned above were carried out in triplicates and were reported as mean ± standard deviation. Analysis of variance (ANOVA) and Duncan's multiple range tests (P≤0.05) were used to test the differences.

## 3. Results and Discussion

### 3.1 Vacuum frying sterilization

The optimal vacuum frying time was selected because of the high oil yield and the desirable appearance of the fried palm fruits. The proper frying improved the oil yield by making pores in the oil micelles, facilitating oil extraction at the subsequent step [16]. It also affects the content of phytonutrients and the sensory characteristics of the oil. Therefore, monitoring and controlling the frying condition is important. Table 1. presented that oil yield increased with frying time. An oil yield of more than 30% was achieved when the frying times reached 90 and 105 min. However, it was observed that increasing the frying time beyond 90 min negatively impacted the characteristics of palm fruits. Excessive frying (105 min) leads to a burning crust, which may contribute to unpleasant flavor, dark color, and toxic compounds. Though further research is required to assess the nutritional value and safety of the oil, this study revealed the frying time of 90 min was optimal for the vacuum sterilization of the palm fruit at a temperature of 80 °C and pressure of -400 to -720 mmHg.

After frying, the fried palm fruits were screw-pressed to extract the oil. The properties of the extracted oils from vacuum fried and steam sterilizations are presented in Table 2. When comparing properties to the specification issued by the Department of Malaysian Standard [17], which we have adopted as our national standard for premium quality crude palm oil, it was revealed that both extracted oils complied with the requirements for melting points, iodine value, and carotenoid contents. Technically, melting point is defined as the temperature at which it changes state from solid fat to liquid oil. Generally, most materials' melting and freezing points are approximately equal but not always the same as the freezing point because nucleating substances are significantly affected [18]. Nevertheless, it was predicted from the similar melting point that both extracted oils tend to have similar fractionation temperatures. However, a precise measurement of their exact fractionation temperatures will be confirmed in the fractionation study.

The iodine value not only reflects fatty acid composition and degree of unsaturation of the oil but can be used to predict some aspects of the crystallization behavior of the oil during the fractionation process. However, the crystallization behavior may be shifted due to the multiple polymorphic transitions that occur during melting and crystallization [19]. In this study, the iodine values of both extracted oils were high. They were close to that of the olein [20], which means there was higher unsaturated triacylglyceride concentrate in the solid fraction, so the lower fractionation temperature was expected.

The steam-sterilized oil contained higher amounts of carotenoids and vitamin E contents. The reason was that the oil obtained from the steam sterilized process was extracted from the mesocarp of the palm fruits, which are rich in carotenoids and vitamin E. In contrast, the vacuum fried oil was derived from whole fruits, including the kernel, which does not contain carotenoids and has a lower level of vitamin E [21].

It was obvious that the phosphorus contents were out of the range specified in the Malaysian standard [17]. Considering that soils in Southeast Asia naturally contain deficient amounts of phosphorus to support palm tree growth, inappropriate fertilizers have been applied, leaving behind a high amount of phosphorus in palm oil [22]. However, the amounts of iron and copper in the extracted oil derived from the vacuum frying sterilization were considerably lower than those obtained from the commercial steam sterilization process. Szydłowska-Czerniak et al. [23] noted that heavy metals in commercial steam sterilized oil could come from equipment, industrial wastes, vehicle exhaust, and chemical treatments.

The oil derived from the vacuum frying sterilization is also of better quality in terms of free fatty acids and peroxide value. The lower level of free fatty acids in the vacuum fried oil was mainly attributed to the better quality of palm fruits. In this case, the accumulation of free fatty acids in the fruits was investigated, and it found that the vacuum frying sterilization plant encountered fewer problems that typically occurred during post-harvesting the palm fruits, such as damaged fruits, delayed delivery, and prolonged storage, as the Chaipattana foundation project well manages the plant. The lower free fatty acids level resulted in a lower neutralizing cost [2, 26] and less destruction of carotenoids during the neutralization process [1]. The result of the peroxide test, which represents the oil's oxidative stability, showed that a higher peroxide value corresponded with a higher content of free fatty acids. In the case of vacuum frying sterilization, the lower peroxide value is contributed by two factors; using good quality palm fruits and frying under vacuum condition that permits a sucking of volatile compounds from the oil [8].

**Table 1.** Effect of frying time on water content, oil yield, and appearance of palm fruits during vacuum frying at a temperature of 80 °C and pressure of -400 to -720 mmHg.

| **Frying time (min)** | **Water content (%)** | **Oil yield (%)** | **Appearance of palm fruits** |
|---|---|---|---|
| 15 | $14.08 \pm 2.52^{a}$ | $19.63 \pm 1.29^{d}$ |  |
| 30 | $11.87 \pm 0.90^{ab}$ | $22.22 \pm 0.87^{c}$ |  |
| 45 | $10.42 \pm 0.80^{b}$ | $24.40 \pm 0.54^{b}$ |  |
| 60 | $9.31 \pm 1.83^{bc}$ | $25.67 \pm 0.95^{b}$ |  |
| 75 | $6.63 \pm 1.43^{c}$ | $27.15 \pm 0.64^{b}$ |  |
| 90 | $5.15 \pm 1.46^{d}$ | $30.35 \pm 0.57^{a}$ |  |
| 105 | $4.34 \pm 1.21^{d}$ | $30.63 \pm 0.63^{a}$ |  |

Note: Mean values within each column followed by different superscript letters (a, b, c, d) were significantly different (P≤0.05).

**Table 2.** Properties of extracted oils derived from vacuum frying sterilization and steam sterilization.

| Properties | Extracted oil derived from vacuum frying sterilization (80 °C , -400 to -720 mmHg, 90 min) | Extracted oil derived from steam sterilization (120-140 °C, 45 min) | Malaysian standard [17] |
|---|---|---|---|
| Melting point (°C) | 33.57 ± 0.83 | 33.75 ± 0.63 | 33.8-39.2 |
| Iodine value (g $I_2$/100g) | 51.37 ± 1.74 | 52.29 ± 2.17 | 50.4-53.7 |
| Carotenoid (mg/kg) | 538.30 ± 10.75 | 639.90 ± 5.3 | 474-689 |
| Free fatty acids (%) | 3.28 ± 0.07 | 4.10 ± 0.14 | NA |
| Peroxide value (meq.$O_2$/kg) | 6.83 ± 0.13 | 8.31 ± 0.08 | NA |
| Phosphorus (mg/kg) | 68.74 ± 0.23 | 111 ± 0.13 | NA |
| Iron (mg/kg) | 8.29 ± 0.02 | 20.27 ± 0.10 | NA |
| Copper (mg/kg) | < 0.1 | 55.56 ± 0.19 | NA |
| $\alpha$-TP (mg/kg) | 244.85 ± 60.49 | 279.46 ± 11.46 | NA |
| δ-TP (mg/kg) | ND | ND | NA |
| $\gamma$-TP (mg/kg) | ND | ND | NA |
| $\alpha$-TT (mg/kg) | 193.37 ± 29.70 | 133.68 ± 11.47 | NA |
| δ-TT (mg/kg) | 46.37 ± 6.56 | 59.45 ± 4.85 | NA |
| $\gamma$-TT (mg/kg) | 249.72 ± 86.38 | 290.54 ± 21.66 | NA |
| Total Vitamin E (mg/kg) | 734.31 ± 9.90 | 763.25 ± 21.75 | NA |

Note: TP-Tocopherol, TT Tocotrienol, ND-Not detected, NA-Not analyzed

**3.2 Degumming and neutralization**

The extracted oils derived from vacuum frying and steam sterilization processes were degummed and then neutralized afterward. Degumming is intended to eliminate gums, phosphatides, and other sticky substances from the oil to improve oil stability and facilitate further processing. This study used acid to dissociate the nonhydratable phosphatides into phosphatidic acid and calcium or magnesium bi-phosphate salt [25]. After that, the sedimented gum was separated from the oil. Therefore, the degumming process led to yield loss and lower residual phosphorous (Table 3).

The main purpose of neutralization is to reduce the free fatty acids accumulated in oils by saponifying acids with an alkaline solution. However, based on the analysis results presented in Table 3, it was revealed that the neutralization procedure used in this study could eliminate free fatty acids, phosphorus, and iron that can function as pro-oxidants. Removing phosphorus and iron from the oil occurred when the oil was washed with warm water to eliminate soap [28, 29]. Similar results were discovered in the oil processed under steam sterilization, as reported by Rakprasoot et al. [26]. It can be stated that the selected degumming and neutralization processes used in this study are by far the most suitable processes as they can be used with the extracted oils of all quality, that is, oil from steam sterilization, which is high in free fatty acids and peroxide value. Besides that, neither process had a high deterioration influence on carotenoids, as shown in Table 3.

**Table 3.** Properties of vacuum-fried crude palm oil after degumming and neutralization processes.

| Properties | Vacuum fried oil | Oil after degumming | Oil after neutralization |
|---|---|---|---|
| Oil yield (%) | 100.00 | 95.78 ± 4.06[a] | 82.77 ± 3.43[b] |
| Carotenoids (mg/kg) | 538.30 ± 10.75[a] | 518.34 ± 11.77[b] | 533.98 ± 12.76[a] |
| Free fatty acid (%) | 3.28 ± 0.07[a] | 3.38 ± 0.18[a] | 0.17 ± 0.07[b] |
| Phosphorus (mg/kg) | 68.74 ± 0.23[a] | 62.9 ± 0.03[b] | ND |
| Iron (mg/kg) | 8.29 ± 0.02[a] | 7.41 ± 0.02[b] | < 0.1 |
| Copper (mg/kg) | < 0.1 | < 0.1 | < 0.1 |

Note: Mean values within each row followed by different superscript letters (a, b) were significantly different (P≤0.05), ND-Not detected

### 3.3 Fractionation

Dry fractionation was used in this study as it is the simplest and cheapest fractional technique [24]. However, when crystallization operates in bulk, the viscosity problem limits crystallization efficiency in one step [27], so multi-step fractionation was employed. Another advantage of the multi-step technique is that it delivers a wide range of red palm fats suitable for different applications. The available crystallization temperatures of the commercial refined palm oil cannot be applied to our oil samples because different components in the solid state may affect crystallization behavior even at the same conditions of cooling. Generally, there are three crystalline points in which oil can solidify [24], and results showed that the crystallization temperatures of the neutralized vacuum fried oil occurred at 34 °C, 27 °C, and 17 °C, respectively. In contrast, those of the steam sterilized oil appeared at 34 °C, 25 °C, and 15 °C, respectively. The shifting was mainly due to the difference in composition of the oil samples. As previously mentioned, the steam-sterilized oil was extracted from the fruit's mesocarp. In contrast, the vacuum-fried oil was extracted from the palm fruit, including palm kernel, with the prominent saturated fatty acid being lauric acid [21]. As a result, the second and the third fat fractions of the vacuum-fried oil contained higher levels of saturated fatty acids. The fat fractions' higher proportion of lauric oil resulted in higher crystallization temperatures (Tables 4 and 5). This study confirmed that the crystallization temperatures of the oil samples depend on the oil's origin.

**Table 4.** Fatty acids are composed of red palm fats and red palm oil produced from the oil processed by vacuum frying sterilization.

| Fatty acids (g/100g) | Red palm fats | | | Red palm oil |
|---|---|---|---|---|
| | First fractionation (34 °C) | Second fractionation (27 °C) | Third fractionation (17 °C) | |
| C6:0 | 0.02 ± 0.00 | 0.03 ± 0.01 | 0.03 ± 0.01 | 0.04 ± 0.00 |
| C8:0 | 0.27 ± 0.03 | 0.33 ± 0.07 | 0.37 ± 0.04 | 0.48 ± 0.08 |
| C10:0 | 0.27 ± 0.04 | 0.31 ± 0.01 | 0.38 ± 0.03 | 0.44 ± 0.05 |
| C12:0 | 3.63 ± 0.53 | 4.57 ± 0.25 | 4.31 ± 0.28 | 5.67 ± 0.11 |
| C14:0 | 2.60 ± 0.12 | 3.05 ± 0.09 | 3.10 ± 0.28 | 2.71 ± 0.29 |
| C15:0 | 0.07 ± 0.01 | 0.05 ± 0.01 | 0.06 ± 0.01 | 0.05 ± 0.01 |
| C16:0 | 54.98 ± 1.19 | 44.28 ± 0.83 | 44.28 ± 1.28 | 35.23 ± 0.25 |
| C16:1 | 0.10 ± 0.01 | 0.12 ± 0.01 | 0.13 ± 0.01 | 0.15 ± 0.01 |
| C17:0 | 0.12 ± 0.02 | 0.12 ± 0.01 | 0.12 ± 0.02 | 0.10 ± 0.01 |
| C18:0 | 4.44 ± 0.17 | 4.84 ± 0.10 | 4.78 ± 0.39 | 3.97 ± 0.07 |
| C18:1 | 26.42 ± 0.43 | 34.12 ± 0.90 | 34.01 ± 1.27 | 40.19 ± 0.29 |

**Table 4.** Fatty acids are composed of red palm fats and red palm oil produced from the oil processed by vacuum frying sterilization. (Continue)

| Fatty acids (g/100g) | Red palm fats | | | Red palm oil |
|---|---|---|---|---|
| | First fractionation (34 °C) | Second fractionation (27 °C) | Third fractionation (17 °C) | |
| C18:1*trans* | 0.02 ± 0.00 | 0.02 ± 0.01 | 0.02 ± 0.01 | 0.02 ± 0.01 |
| C18:2 | 6.32 ± 0.10 | 7.26 ± 0.08 | 7.52 ± 0.61 | 9.97 ± 0.33 |
| C18:3 | 0.18 ± 0.04 | 0.25 ± 0.03 | 0.22 ± 0.03 | 0.32 ± 0.04 |
| C20:0 | 0.31 ± 0.10 | 0.39 ± 0.05 | 0.35 ± 0.10 | 0.33 ± 0.02 |
| C20:1 | 0.10 ± 0.05 | 0.11 ± 0.01 | 0.13 ± 0.05 | 0.14 ± 0.01 |
| C20:2 | 0.02 ± 0.00 | 0.03 ± 0.00 | 0.05 ± 0.01 | 0.05 ± 0.01 |
| C22:0 | 0.06 ± 0.01 | 0.06 ± 0.01 | 0.06 ± 0.00 | 0.06 ± 0.01 |
| C24:0 | 0.07 ± 0.01 | 0.07 ± 0.00 | 0.07 ± 0.01 | 0.08 ± 0.01 |
| Unsaturated fatty acids | 33.16 ± 0.55 | 41.92 ± 0.95 | 42.08 ±0 .41 | 50.84 ± 0.50 |
| Saturated fatty acids | 66.84 ± 0.61 | 58.08 ± 0.91 | 57.92 ± 0.39 | 49.16 ± 0.54 |

**Table 5.** Fatty acid compositions of the red palm fats and red palm oil produced from the oil processed by steam sterilization.

| Fatty acids (g/100g) | Red palm fats | | | Red palm oil |
|---|---|---|---|---|
| | First fractionation (34 °C) | Second fractionation (25 °C) | Third fractionation (15 °C) | |
| C8:0 | 0.01 ± 0.00 | 0.01 ± 0.00 | 0.01 ± 0.00 | 0.01 ± 0.00 |
| C10:0 | 0.06 ± 0.01 | 0.03 ± 0.01 | 0.03 ± 0.01 | 0.05 ± 0.01 |
| C12:0 | 0.12 ± 0.02 | 0.13 ± 0.01 | 0.14 ± 0.01 | 0.15 ± 0.01 |
| C14:0 | 1.03 ± 0.07 | 1.08 ± 0.13 | 1.04 ± 0.01 | 0.91 ± 0.02 |
| C15:0 | 0.06 ± 0.01 | 0.04 ± 0.01 | 0.05 ± 0.01 | 0.04 ± 0.01 |
| C16:0 | 50.97 ± 0.44 | 45.11 ± 0.23 | 44.32 ± 0.47 | 38.27 ± 0.45 |
| C16:1 | 0.11 ± 0.01 | 0.14 ± 0.01 | 0.14 ± 0.01 | 0.16 ± 0.01 |
| C17:0 | 0.11 ± 0.01 | 0.12 ± 0.01 | 0.12 ± 0.01 | 0.10 ± 0.02 |
| C18:0 | 5.25 ± 0.38 | 4.84 ± 0.49 | 4.97 ± 0.11 | 4.49 ± 0.06 |
| C18:1 | 32.82 ± 0.75 | 37.96 ± 0.55 | 38.62 ± 0.37 | 43.54 ± 0.68 |
| C18:1*trans* | 0.03 ± 0.00 | 0.03 ± 0.01 | 0.03 ± 0.00 | 0.03 ± 0.01 |
| C18:2 | 8.45 ± 0.23 | 9.54 ± 0.12 | 9.53 ± 0.21 | 11.18 ± 0.17 |
| C18:3 | 0.24 ± 0.05 | 0.24 ± 0.03 | 0.25 ± 0.01 | 0.32 ± 0.02 |
| C20:0 | 0.39 ± 0.02 | 0.38 ± 0.04 | 0.38 ± 0.01 | 0.37 ± 0.01 |
| C20:1 | 0.12 ± 0.02 | 0.14 ± 0.01 | 0.13 ± 0.01 | 0.16 ± 0.01 |
| C20:2 | 0.07 ± 0.01 | 0.07 ± 0.01 | 0.07 ± 0.01 | 0.07 ± 0.01 |
| C22:0 | 0.07 ± 0.01 | 0.06 ± 0.01 | 0.07 ± 0.00 | 0.06 ± 0.01 |
| C23:0 | 0.01 ± 0.01 | 0.02 ± 0.01 | 0.02 ± 0.00 | 0.02 ± 0.00 |
| C24:0 | 0.07 ± 0.01 | 0.07 ± 0.01 | 0.07 ± 0.00 | 0.07 ± 0.01 |
| Unsaturated fatty acids | 41.84 ± 0.87 | 48.11 ± 0.44 | 48.78 ± 0.53 | 55.46 ± 0.56 |
| Saturated fatty acids | 58.16 ± 0.82 | 51.90 ± 0.40 | 51.23 ± 0.58 | 44.54 ± 0.51 |

### 3.4 Properties of red palm oil and red palm fats produced from the vacuum frying process

As the main purpose of this research was to develop an effective red palm oil processing method suitable for SMEs, properties analysis of the end products was performed only on those derived from the vacuum frying process. Analysis results are shown in Tables 6 and 7. Yield is important when developing a new process, as yield can significantly impact the business's profit. The yield of red palm oil obtained from the vacuum frying process was 61%, more than that from the steam sterilization process (53.45%) [14]. As important as yield, concentrations of carotenoids and vitamin E in the red palm oil obtained from the triple fractionation increased by about 15% and 14%, respectively, compared to the contents in the extracted oils (Table 2). The main form of vitamin E in red palm oil is tocotrienol, especially in the form of $\gamma$-tocotrienol, which has potent antioxidant, anti-inflammatory and neuroprotective activities [28]. The higher content of these phytonutrients would favor positive claims on the nutritional label. Greater concentrations of carotenoids derived from the multi-step fractionation compared to the non-fractionated oil have been reported [18]. The result also showed that the increase of carotenoids and vitamin E concentrations positively related to increased red palm fats and oil iodine values. Previous work reported that the dissolving of both compounds is based on the principle of similar phase solubility [29]. In this case, the temperature at the end of the fractionation process was 15 °C. Carotenoids and vitamin E that have freezing points of less than -20 °C [30] and -27.5 °C [31], respectively, still appeared in the liquid form. Thus, the solubility of carotenoids and vitamin E increased with the degree of unsaturation of the liquid fraction (red palm oil >first red palm fat >second red palm fat >third red palm fat). Comparing parameter quality (Table 6) with other research (Table 7) [36-38] showed that the developed vacuum-fried method could be used to produce good-quality red palm oil.

For red palm fats, differences in properties such as iodine value, melting point, and solid fat content (Table 6, 8) enable red palm fats to be tailor-made for many applications. According to the solid fat content and melting point, the important information for characterizing fats used in the bakery, confectionery, and margarine industries, the first red palm fat with low iodine value might be used as a confectionery ingredient [24]. Meanwhile, the second and third red palm fats with medium and high iodine values can produce margarine and cacao butter substitutes, respectively [18]. Another main characteristic of red palm fats is their nutritional and functional properties due to their fair carotenoids and vitamin E contents. This property certainly responds to the demand for healthy fat products.

**Table 6.** Properties of red palm fats and red palm oil produced from the vacuum fried oil.

| Properties | First red palm fat | Second red palm fat | Third red palm fat | Red palm oil |
|---|---|---|---|---|
| Yield (%) | 14.54 ± 2.70$^{b}$ | 13.94 ± 2.36$^{bc}$ | 10.21 ± 0.93$^{c}$ | 61.31 ± 1.82$^{a}$ |
| Iodine value (g $I_2$/100g) | 36.90 ± 3.03$^{d}$ | 41.94 ± 2.27$^{c}$ | 49.27 ± 0.05$^{b}$ | 62.06 ± 0.14$^{a}$ |
| Free fatty acids (%) | 0.16 ± 0.02$^{a}$ | 0.17 ± 0.02$^{a}$ | 0.17 ± 0.02$^{a}$ | 0.17 ± 0.03$^{a}$ |
| Peroxide value (meq. $O_2$/kg) | 6.40 ± 0.14$^{a}$ | 6.54 ± 0.07$^{a}$ | 6.65 ± 0.07$^{a}$ | 6.70 ± 0.13$^{a}$ |
| Melting point (°C) | 53.2 ± 0.3$^{a}$ | 43.5 ± 0.1$^{b}$ | 37.1 ± 0.3$^{c}$ | NA |
| Carotenoids (mg/kg) | 321.90 ± 34.81$^{d}$ | 382.18 ± 37.31$^{c}$ | 417.69 ± 19.64$^{c}$ | 620.34 ± 9.90$^{a}$ |
| $\alpha$-TP (mg/kg) | 200.75 ± 16.90$^{b}$ | 205.07 ± 16.60$^{b}$ | 209.14 ± 18.29$^{b}$ | 263.31 ± 42.57$^{a}$ |
| δ-TP (mg/kg) | ND | ND | ND | ND |
| $\gamma$-TP (mg/kg) | ND | ND | ND | ND |
| Total TP (mg/kg) | 200.75 ± 16.90$^{c}$ | 205.07 ± 16.60$^{cd}$ | 209.14 ± 18.29$^{b}$ | 263.31 ± 42.57$^{a}$ |
| $\alpha$-TT (mg/kg) | 154.29 ± 7.81$^{c}$ | 155.85 ± 13.63$^{c}$ | 186.69 ± 11.40$^{b}$ | 221.48 ± 10.44$^{a}$ |
| δ-TT (mg/kg) | 16.31 ± 2.29$^{c}$ | 19.00 ± 3.57$^{c}$ | 26.00 ± 2.95$^{b}$ | 49.95 ± 5.67$^{a}$ |
| $\gamma$-TT (mg/kg) | 64.37 ± 12.23$^{d}$ | 84.70 ± 16.27$^{c}$ | 117.54 ± 28.50$^{b}$ | 300.30 ± 56.06$^{a}$ |
| Total TT (mg/kg) | 234.97 ± 6.55$^{c}$ | 259.55 ± 13.06$^{c}$ | 330.23 ± 26.03$^{b}$ | 571.73 ± 50.77$^{a}$ |
| Total Vitamin E (mg/kg) | 435.71 ± 10.40$^{d}$ | 464.62 ± 8.55$^{c}$ | 539.37 ± 12.10$^{b}$ | 835.04 ± 23.06$^{a}$ |

Note: Mean values within each row followed by different superscript letters (a, b, c, d) were significantly different ($P \leq 0.05$), TP-Tocopherol, TT-Tocotrienol, ND-Not detected, NA-Not analyzed

**Table 7.** Fatty acid contents and properties of vacuum-fried red palm oil and commercial red palm oils

| Properties and fatty acids (g/100g) | Red palm oil derived from the vacuum frying process | Commercial red palm oils | | |
|---|---|---|---|---|
| | | Boon et al., [32] | El-Hadad et al., [33] | Bonnie & Choo., [34] |
| Free fatty acids (%) | 0.17 ± 0.03 | NA | 0.12 ± 0.02 | NA |
| Peroxide value (meq. $O_2$/kg) | 6.70 ± 0.13 | NA | 1.5 ± 0.22 | NA |
| Iodine value (g $I_2$/100g) | 62.06 ± 0.1 | NA | 56.7 ± 0.42 | NA |
| C12:0 | 0.15 ± 0.01 | 0.0 | 0.2 | 0.25 |
| C14:0 | 0.91 ± 0.02 | 1.2 | 0.9 | 1.07 |
| C16:0 | 38.27 ± 0.45 | 39.5 | 39.3 | 36.6 |
| C16:1 | 0.16 ± 0.01 | 0.0 | 0.2 | NA |
| C17:0 | 0.10 ± 0.02 | NA | 0.1 | NA |
| C18:0 | 4.49 ± 0.06 | 3.7 | 4.2 | 3.7 |
| C18:1 | 43.54 ± 0.68 | 43.5 | 43.7 | 46.7 |
| C18:2 | 11.18 ± 0.17 | 12.2 | 10.5 | 12.8 |
| C18:3 | 0.32 ± 0.02 | 0.0 | 0.5 | NA |
| C20:0 | 0.37 ± 0.01 | 0.0 | 0.4 | NA |
| Unsaturated fatty acids | 55.46 ± 0.56 | 55.6 | 54.9 | 59.5 |
| Saturated fatty acids | 44.54 ± 0.51 | 44.4 | 45.1 | 41.62 |
| Carotenoids (mg/kg) | NA | 564 | 580 | 665 |
| Vitamin E (mg/kg) | 835.04 ± 23.06 | 1,141 | 820 | 717–863 |

Note: NA-Not analyzed

**Table 8.** Solid fat contents of the red palm fats.

| Temperature (°C) | Solid fat contents | | |
|---|---|---|---|
| | First, red palm fat | Second, red palm fat | Third, red palm fat |
| 10 | 74.48 ± 0.33 | 62.85 ± 0.65 | 60.33 ± 0.49 |
| 15 | 66.90 ± 0.15 | 51.78 ± 0.11 | 50.37 ± 0.34 |
| 20 | 57.42 ± 0.08 | 38.03 ± 0.15 | 37.22 ± 0.17 |
| 25 | 46.83 ± 0.04 | 25.69 ± 0.18 | 22.94 ± 0.17 |
| 30 | 37.31 ± 0.05 | 17.17 ± 0.07 | 13.28 ± 0.05 |
| 35 | 29.30 ± 0.24 | 11.48 ± 0.16 | 6.96 ± 0.10 |
| 40 | 22.87 ± 0.16 | 6.81 ± 0.18 | 2.00 ± 0.03 |
| 45 | 16.54 ± 0.76 | 3.23 ± 0.19 | 0.22 ± 0.10 |

### 3.4 Consumer acceptance test

#### *3.4.1 The red palm oils*

The refined palm oil had the highest score in all sensory attributes, followed by the red palm oils produced from the vacuum sterilization and the steamed sterilization processes, respectively ($P \leq 0.05$) (Table 9). This study suggested that consumers prefer the colorless and odorless oil more than the oil with a red color and distinctive nutty flavor. Nevertheless, red palm oil may move from a niche to a widespread commercial oil depending on validation of the health benefits and its various applications. Nevertheless, the panelists prefered vacuum-fried red palm oil for all attributes over steam-sterilized red palm oil. Thus, the vacuum frying method could overcome problems regarding off-flavor and off-odor commonly existing in steam-sterilized oil. This conclusion agreed with the previous study that vacuum frying could effectively remove the volatile compounds from the oil [35].

**Table 9.** Sensory scores of oil samples.

| Attributes | Commercial refined palm oil (Control) | Red palm oils | |
|---|---|---|---|
| | | Vacuum frying sterilization | Steam sterilization |
| Appearance | 7.78 ± 0.83[a] | 6.94 ± 1.08[b] | 6.82 ± 1.00[b] |
| Clearness | 8.12 ± 0.74[a] | 7.46 ± 1.07[b] | 7.30 ± 1.29[b] |
| Color | 7.88 ± 0.79[a] | 6.82 ± 1.27[b] | 6.72 ± 1.18[b] |
| Odor | 7.43 ± 1.17[a] | 6.20 ± 0.95[b] | 5.64 ± 1.04[c] |
| Overall acceptability | 7.73 ± 0.80[a] | 6.60 ± 0.92[b] | 6.26 ± 0.96[b] |

Note: Mean values within each row followed by different superscript letters (a, b c) were significantly different ($P \leq 0.05$), and the scores were the nine-point hedonic scales ranging from 1 = Dislike extremely and 9 = Like extremely.

### *3.4.2 The deep-fried potato sticks*

This study aimed to comprehensively examine the application of red palm oils in deep frying. The appearances of deep-fried potato sticks or French fries were shown in Figure 3, and sensory scores were presented in Table 10. The panelists rated all the sensory characteristics of the control, and the sample was fried in vacuum-fried red palm oil from slightly to moderately. Both samples had the highest scores for their odors. This result suggested that the vacuum condition applied during the sterilization step effectively eliminates the off-odor compounds. For color attribute, it was revealed that carotenoid pigment in red palm oils was practically stable throughout the frying period. It was shown to absorb in the fried samples, leading to lower appearance scores. Compared with others, the potato fried in the steam-sterilized red palm oil obtained less acceptance in all attributes and had the lowest score for crispness. According to Kita et al. [36], the composition of frying oils' fatty acids affected the crispiness of the fried products. In this case, the higher unsaturated fatty acids of the steam-sterilized red palm oil led to a greasy texture, reducing the crispiness of the French fries. In conclusion, the overall acceptance scores indicated the potential efficacy of using red palm oil derived from the vacuum frying sterilization method as an alternative for replacing oil.


**Figure 3.** Appearances of potato sticks fried in refined palm oil (a), vacuum-fried red palm oil (b), steam sterilized red palm oil (c).

**Table 10.** Sensory scores of the potato sticks deep-fried in refined palm oil and red palm oils

| Attributes | Refined palm oil (Control) | Red palm oil | |
|---|---|---|---|
| | | Vacuum frying sterilization | Steam sterilization |
| Appearance | 7.10 ± 1.18[a] | 6.74 ± 0.96[a] | 6.74 ± 1.17[a] |
| Odor | 7.44 ± 1.05[a] | 7.02 ± 1.12[ab] | 6.78 ± 1.27[b] |
| Flavor | 7.22 ± 1.11[a] | 6.30 ± 0.84[b] | 6.12 ± 1.21[b] |
| Crispiness | 6.42 ± 0.67[a] | 6.16 ± 0.76[a] | 5.64 ± 0.78[b] |
| After taste | 6.70 ± 1.16[a] | 6.22 ± 0.91[b] | 5.86 ± 0.99[b] |
| Overall acceptability | 6.90 ± 0.97[a] | 6.24 ± 0.89[b] | 5.90 ± 0.93[b] |

Note: Mean values within each row followed by different superscript letters (a, b c) were significantly different (P≤0.05).

## 4. Conclusion

The overall results of this study indicated that combined vacuum frying sterilization and multi-step fractionation is a practical approach for producing red palm oil and red palm fats. Vacuum frying sterilization contributes to red palm oil's high-quality and pleasant odor. At the same time, the multi-step fractionation allows the production of a wide range of red palm fats that have many potential applications in the food industry. The presence of carotenoids and vitamin E in red palm oil and red palm fats would promote palm oil as an attractive option for health-conscious consumers. Unlike conventional steam sterilization, this cost-saving and environmentally friendly process suits small to medium-sized operations.

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