Vol. 14, No. 1 (2025): 215 - 225 http://dx.doi.org/10.23960/jtep-l.v14i1.215-225

JURNAL TEKNIK PERTANIAN LAMPUNG

ISSN 2302-559X (print) / 2549-0818 (online)
Journal homepage : https://jurnal.fp.unila.ac.id/index.php/JTP

Impact of High-Temperature Heating on the Chemical Stability and Sensory Quality of Red Palm Oil

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Article History:

Received : 06 June 2024
Revised : 17 July 2024
Accepted : 07 September 2024

Keywords:

Nutritional value,
Prolonged heating,
Red palm oil,
Sensory attributes,
Thermal oxidation,

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ABSTRACT

Red palm oil (RPO) is known for its high carotenoid content, particularly β-carotene and α-carotene, which provide significant provitamin A activity. However, it is susceptible to oxidation during frying and results in nutrient loss and quality degradation. This study investigates the effects of high temperatures and prolonged heating durations on the chemical and sensory properties of RPO. The experiment involved heating RPO at three different temperatures (140°C, 180°C, and 220°C) for durations ranging from 2 to 10 hours. Chemical analysis included peroxide values, free fatty acids, and changes in functional groups through Fourier-Transform Infrared (FTIR) spectroscopy. Sensory evaluations focused on aroma and color alterations due to heating. Results showed that prolonged heating of RPO at high temperatures led to significant increase in peroxide values, and the formation of oxidation products, including aldehydes and ketones, which negatively impacted the sensory qualities. The oil darkened, and a burnt aroma developed, reducing overall sensory appeal. These findings provide new insights into the optimal frying conditions to preserve the nutritional and sensory qualities of RPO, particularly by minimizing heating duration and temperature.

1. INTRODUCTION

Red palm oil (RPO) is derived from the mesocarp of the oil palm fruit and retains its vibrant red color due to minimal processing, such as the avoidance of bleaching or high-temperature exposure. This oil is notable for its significantly high carotenoid content, which is 15 times higher than that of carrots and 300 times higher than tomatoes (Nagendran *et al*., 2000). Although fried foods are popular due to their ease of preparation, heating oil at high temperatures induces various physical, physicochemical, and chemical changes. These include the formation of harmful compounds such as peroxides, aldehydes, ketones, free radicals, and trans fatty acids, which alter the flavor, color, and aroma of oil. Prolonged heating leads to the breakdown of essential components like β-carotene, tocopherol, and other minor constituents (Li *et al*., 2017). Despite its nutrient density, RPO is susceptible to thermal oxidation during frying, resulting in the formation of degradation products such as aldehydes, ketones, acids, alcohols, and polymers. Heating oils beyond a certain temperature threshold alters their physicochemical properties (Oboh *et al*., 2014; Falade & Oboh, 2015). Cooking oil is used repeatedly in the cooking process at high temperatures (Elaine *et al*., 2022), where various chemical reactions such as hydrolysis, oxidation, polymerization, and isomerization occur which can reduce the quality of cooking oil (Herlina *et al*., 2017). Repeated use of cooking oil can cause a decrease in quality as seen from the increase in saturated fatty acid components and changes in the color of cooking oil (Rahayu & Purnavita, 2014). Heating cooking oil at high temperatures can increase free fatty acid components, peroxide numbers, cooking oil color index and reduce the iodine number which indicates a decrease in the quality of cooking oil (Al Amin *et al*., 2023; Husain & Marzuki, 2021; Nugroho *et al*., 2014; Pramitha *et al*., 2022).

The final product fried in damaged oil has an unpleasant taste, odor and texture (Tena *et al*., 2009). While prior studies have examined the impact of heating on carotenoid content up to 180°C, the influence of higher temperatures on the sensory, chemical, and functional properties of RPO remains unexplored (Budiyanto, 2010). Previous research has provided valuable insights into the effects of heating on RPO, particularly regarding carotenoid degradation at temperatures up to 180°C (Budiyanto, 2010). However, there remains a significant gap in understanding how higher temperatures and extended heating durations influence the sensory characteristics and chemical composition of RPO. Most studies have focused on the general degradation of carotenoids and the increase in peroxide values due to thermal oxidation during frying, but little attention has been paid to the specific changes in the functional groups and the overall quality of RPO when subjected to extreme heat. Moreover, the majority of existing literature has emphasized conventional oils rather than RPO, despite its higher carotenoid content and susceptibility to oxidative damage (Jatmika & Guritno, 1997). This leaves a critical gap in understanding how the unique composition of RPO reacts under different frying conditions, particularly at temperatures exceeding 180°C. Addressing this gap is essential to optimize its use in cooking while preserving its nutritional value.

This study presents a novel investigation into the effects of high temperatures and prolonged heating on the chemical and sensory properties of RPO. Unlike previous studies that have primarily focused on conventional oils or lower-temperature conditions, this research examines the impact of extreme heat on the functional groups, oxidation levels, and sensory attributes of RPO. By exploring temperatures beyond 180°C and evaluating both volatile and non-volatile degradation products, this study aims to provide a comprehensive understanding of how RPO behaves under various frying conditions. The findings will offer new insights into optimizing frying practices to maintain the nutritional quality and sensory appeal of oil, addressing a crucial knowledge gap in the current body of research (Budiyanto, 2010). Therefore, this study aims to investigate the effects of temperature and heating duration on the chemical and sensory properties of RPO.

2. RESEARCH AND METHODS

2.1. Materials and Equipment

The materials used in this study include RPO purchased online without a specific brand, glacial acetic acid, chloroform, potassium iodide (KI), sodium thiosulfate ($Na_2S_2O_3$), carbon tetrachloride (CCl_4), Wijs solution, phenolphthalein (PP), 95% ethanol, sodium hydroxide (NaOH), and potassium hydroxide (KOH). The equipment used includes Pyrex Erlenmeyer flasks, burettes, a Fourier-transform infrared spectroscopy (FTIR) device (Carry 639 FTIR, Agilent), and a gas chromatograph (GC) for saturated fat analysis (Clarus 580).

2.2. Research Design and Procedure

This study was conducted using a factorial experiment arranged in a Completely Randomized Block Design (CRBD) with three replications. The factors include heating temperatures (S), which are: (S1) 140°C, (S2) 180°C, and (S3) 220°C, and heating durations (L), which consist of: L1 (2 hours), L2 (4 hours), L3 (6 hours), L4 (8 hours), and L5 (10 hours). The data were analyzed using analysis of variance (ANOVA) and orthogonal polynomial comparisons at significance levels of 1% and 5%.

A total of 1500 ml of olein was heated in a Pyrex beaker at temperatures of 50°C, 100°C, 150°C, 200°C, and 250°C for 5, 10, 15, 20, and 25 hours. After each heating cycle, the samples were cooled to room temperature overnight. Samples were taken for analysis after each heating and cooling cycle and stored in a freezer (-4°C) until use. The parameters observed in this study included: Peroxide value AOCS Cd 8b-90 method (AOCS, 2005), Free fatty acids according to SNI-2901-2021 (BSN, 2021), Functional group analysis performed using FTIR (Al Degs *et al*., 2011) and sensory analysis included scoring and hedonic tests for color and aroma. For sensory evaluation, 20 panelists assessed the aroma and color attributes of the RPO. In the color scoring test, scores were assigned as follows: 5 (red), 4 (reddish-brown), 3 (brown), 2 (brownish-black), and 1 (black). For aroma scoring, the scale was: 5 (typical RPO smell), 4 (slightly typical RPO smell), 3 (slightly burnt smell), 2 (burnt smell), and 1 (strong burnt smell). The hedonic test assessed the overall preference for RPO, with scores ranging from 5 (strongly like), 4 (like), 3 (neutral), 2 (dislike), to 1 (strongly dislike).

3. RESULT AND DISCUSS

3.1. Free Fatty Acids (FFA)

Free fatty acids (FFA) are the result of oil or fat degradation. In this study, the FFA levels in RPO after heating ranged from 0.912% to 1.387%. Heating RPO led to a decrease in FFA content, particularly at 140°C and 180°C, across heating durations of 2, 4, 6, 8, and 10 hours. The trend of FFA levels is depicted in Figure 1. Various frying studies have shown that the increase in FFA levels is influenced by water content, oil type, and other components in the material that can react with FFAs in vegetable oils (Gerde *et al*., 2007). However, in this study, no external materials were added to the RPO. A similar reduction in FFA content was reported during the deodorization of RPO (Budiyanto *et al*., 2007). While the FFA content decreased slightly during heating, the initial two hours of heating generally increased FFA levels. Beyond two hours, FFA levels decreased with extended heating times (up to 10 hours), across various temperatures. This reduction occurs when the rate of FFA formation is slower than the degradation or conversion of FFAs into volatile compounds (Budiyanto *et al*., 2007).

Moreover, the presence of β-carotene, an antioxidant, may slow down FFA production during heating. The unstable double bonds in β-carotene structure make it reactive with FFAs (Henon *et al*., 1997). The degradation of carotenoids in RPO could produce volatile compounds and other degradation products that do not register as FFAs (Jatmika & Guritno, 1997; Okiy & Oke, 1986; Sahidin *et al*., 2000). The breakdown of β-carotene and other degradation products, as well as the formation of volatile compounds due to heating, likely accelerates FFA breakdown (Manurung *et al*., 2018). The FFA values in this study exceed the SNI 3741:2013 standard (BSN, 2013), which sets the allowable FFA value at ≤0.3%, indicating excessive hydrolysis or oxidation (Legasari *et al*., 2023).

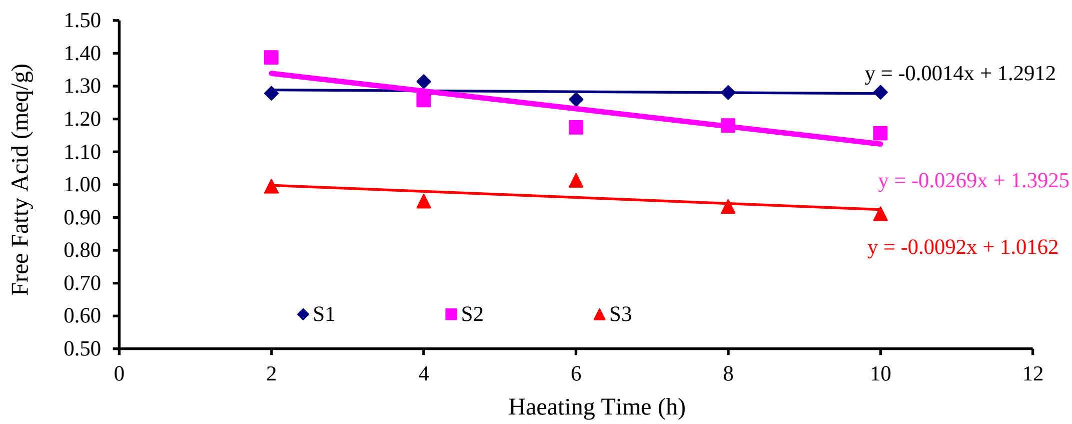

Figure 1. Effect of heating temperature and heating time on the free fatty acid content of RPO

3.2. Peroxide Value

The peroxide value is a critical parameter for determining the degree of oil and fat damage. In this study, the peroxide values of RPO after heating ranged from 0.79 meq/kg to 1.25 meq/kg. Heating at 140°C and 180°C for 2 to 8 hours resulted in a decrease in peroxide value, while fluctuations occurred during longer heating periods of up to 10 hours (Figure 2). RPO heated to higher temperatures tended to show lower peroxide values after 10 hours of heating. At elevated temperatures, peroxides decompose more rapidly into other compounds (Berger, 1985). Ghazali *et al*. (2006) reported that hydroperoxides form during the first 100 hours of heating at 135°C, particularly in dark conditions, due to the oxidation of unsaturated fatty acids. The peroxide value initially increases as hydroperoxides form, then decreases as they decompose into secondary products. The decline in peroxide values during prolonged heating suggests that peroxide formation occurs more slowly than the decomposition of peroxides into other compounds. This process may be aided by the high β-carotene content, which acts as an antioxidant, delaying peroxide formation (Budiyanto *et al*., 2007). Additionally, other antioxidants in RPO may also contribute to limiting the increase in peroxide levels during heating. According to Sobhani *et al*. (2018), heating significantly increases the peroxide number due to the oxidation reaction that can form hydroxyperoxide compounds. The peroxide number will increase with increasing temperature until it reaches a maximum value, but the peroxide number will decrease after reaching the maximum value (Gao *et al*., 2020). According to SNI 3741:2013 (BSN, 2013), the maximum allowable peroxide value for frying oil is 10 meq O_2/kg, and the lower the peroxide value, the better the oil quality.

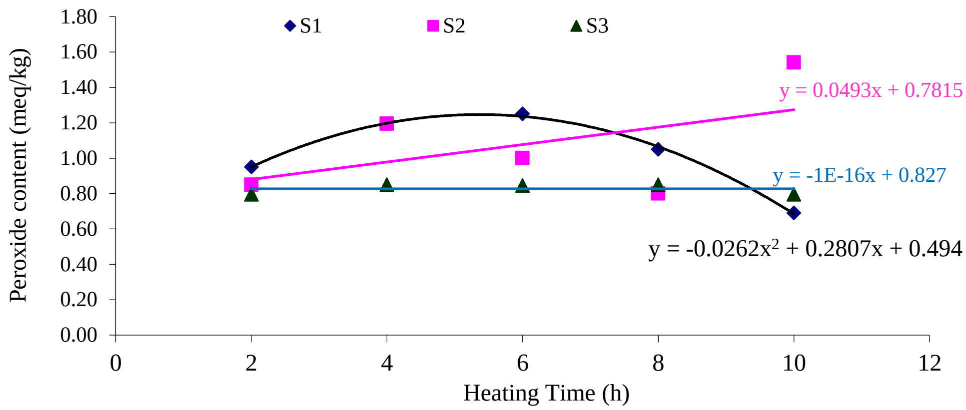

Figure 2. Effect of heating temperature and heating time on the peroxide content of RPO

3.3. FTIR Analysis

Fourier-transform infrared spectroscopy (FTIR) is a fast, simple, and non-destructive technique that allows the identification of chemical properties in samples based on their absorption spectra (Puspitasari *et al*., 2021). FTIR analysis was performed in the infrared wavelength range of 4000–600 cm⁻¹ (Figures 3, 4, and 5). The absorption spectrum of RPO exhibited several functional groups at different wave numbers (Table 1). For example, the O-H group, indicative of phenols and alcohols, was detected at 3742.24 cm⁻¹ and 3734.79 cm⁻¹, with varying intensities. Strong C-H alkane groups were observed between 2922.23 cm⁻¹ and 2847.68 cm⁻¹. C=C alkyne groups appeared at 2363.13 cm⁻¹, while C=O functional groups corresponding to aldehydes, ketones, carboxylic acids, and esters were present at 1744.39 cm⁻¹. Aromatic C-C groups were found at 1461.11 cm⁻¹, and C-O functional groups were detected between 1162.92 cm⁻¹ and 1162.99 cm⁻¹, indicative of alcohols, esters, and carboxylic acids.

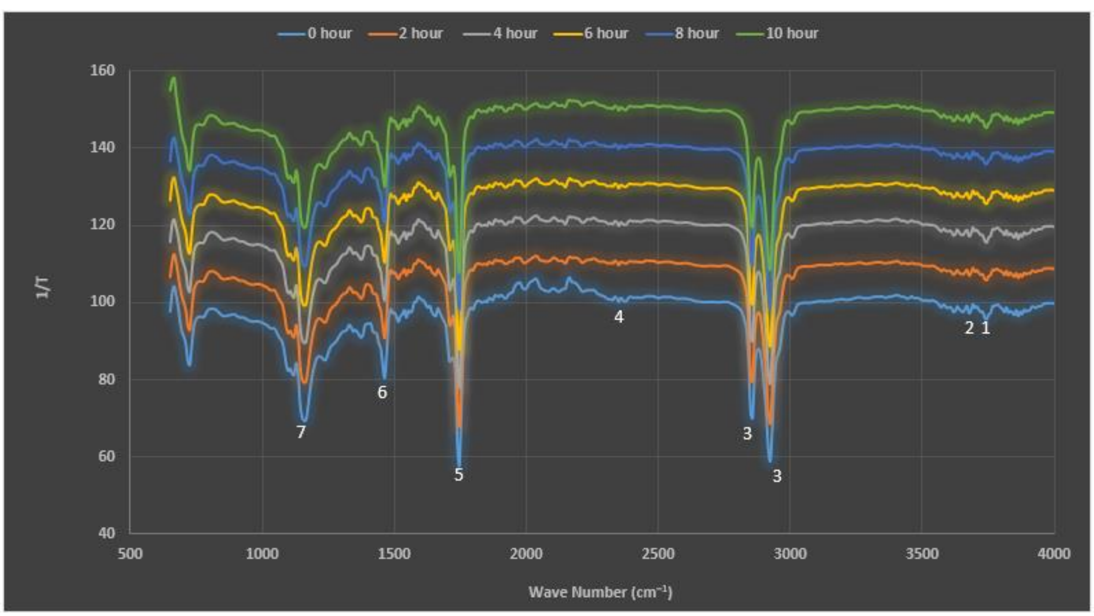

Figure 4. Absorbance spectrum of RPO heated at 140°C with heating times of 2 h to 10 h.

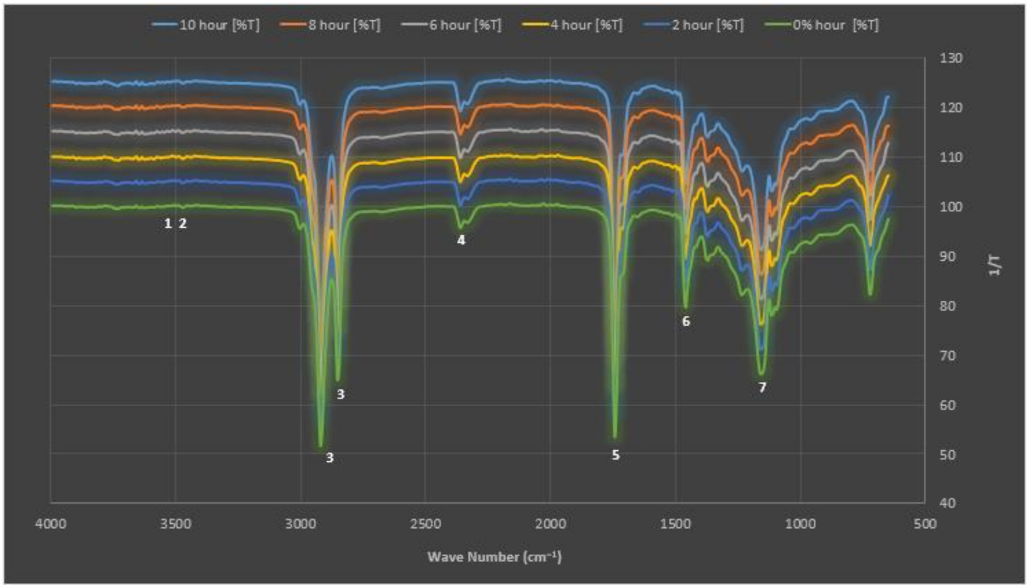

Figure 5. Absorbance spectrum of RPO heated at 180°C with heating times of 2 h to 10 h.

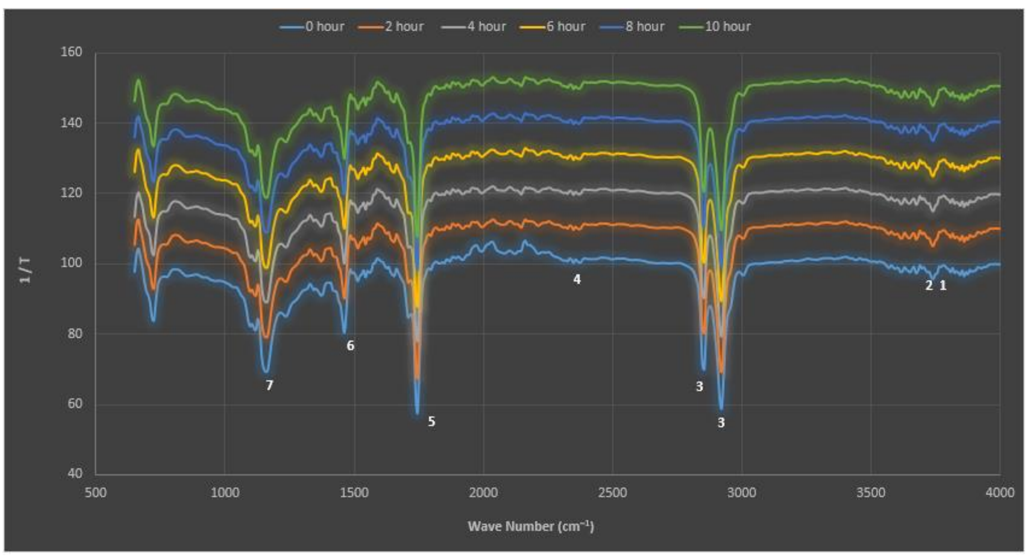

Figure 6. Absorbance spectrum of RPO heated at 220°C with heating times of 2 h to 10 h.

Table 1. Functional groups and FTIR wave numbers of RPO

No	Functional Group	Wave Number (cm^{-1})	1/T		
			140°C	180°C	220°C
1	O-H phenol, Hydrogen bond	3742.24		95.68	95.68
2	Alcohol, Phenol	3734.79	96.09		
3	C-H Alkane (strong)	2922.23	58.87	51.64	58.87
		2855.14	69.97	65.02	
		2847.68			71.24
4	C=C Alkuna	2363.13		95.64	
5	C=O Aldehidyde, Ketones, carboxylic acid, Esters (strong)	1744.39	53.55	57.66	57.66
6	C-C Senyawa Aromatic	1461.11		80.42	80.42
7	C-O Alkohol, Ester, carboxylic acid, Esters (strong)	1162.92	69.49		69.48

3.4. Aroma Scoring

The aroma of RPO after heating ranged from 3.0 (slightly burnt) to 4.0 (slightly characteristic of RPO). Higher temperatures and longer heating times led to a burnt aroma, as shown in Figure 7. The off-flavors were likely due to volatile compounds such as aldehydes, ketones, hydrocarbons, and alcohols formed during oxidation (Kemp *et al*., 2009; Marantika, 2016). Figure 7 shows a decrease in the aroma score of RPO after heating with increasing temperature and heating time. The aroma of RPO after heating experiences a change in flavor or smell. This is due to several influencing factors, namely temperature, light/irradiation, availability of oxygen and the presence of metals that act as catalysts in the oxidation process. If the heating temperature is higher, the oil will become rancid. Rancidity in oil/fat can occur due to oxidation, enzymes and hydrolysis processes. When oil is heated to a temperature of ≥ 200°C, volatile components such as aldehydes, ketones, hydrocarbons, alcohols, acids and esters will be formed. These volatile components are formed from the results of oxidation reactions in the oil which then form hydroperoxides which then decompose. The formation of these volatile components is influenced by the type of oil/fat, temperature and heating time (Marantika, 2016).

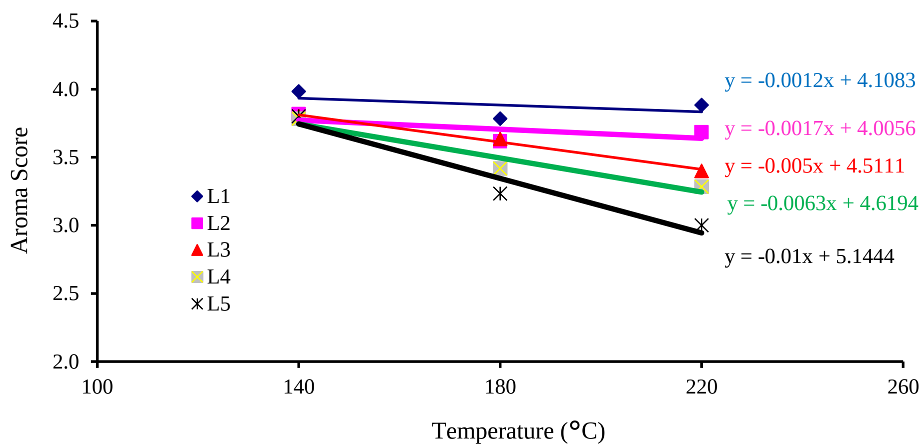

Figure 7. Effect of heating temperature and heating duration on the aroma scoring of RPO after heating

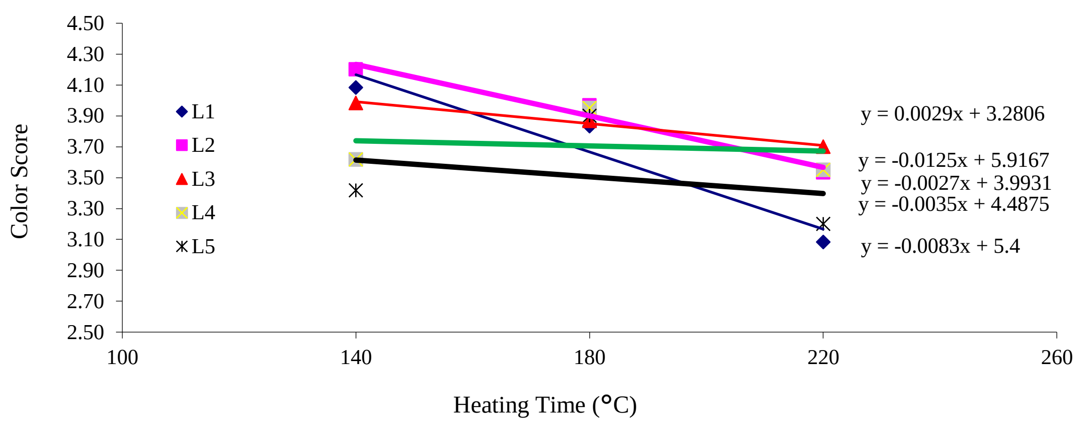

Figure 8. Effect of heating temperature and heating duration on the color scoring of RPO after heating

3.5. Color Scoring

Color is a sensation produced by light waves received by the retina of the eye. The results of observations from each color scoring treatment after heating RPO ranged from 3.1 (brown) to 4.2 (reddish brown). The heating temperature and the interaction between the heating temperature and the heating duration caused the color of the RPO after heating to change from reddish brown to brown. Figure 7 shows that at a heating temperature of 140°C, the degree of color of palm oil began to decrease with a heating duration of 4 h to 10 h. While at heating of 180°C and 220°C the color of the oil was stable without experiencing much color change. High heating temperatures can cause the color of the oil to become darker due to several factors, including the vitamins contained in the oil being oxidized, both carotenoids that are soluble in oil due to the oxidation process and oxidation of tocopherol (vitamin E). In addition, at high heating temperatures, fatty acids, sterols, and hydrocarbons produced from triglyceride hydrolysis can break down and dissolve or mix in the oil so that the color of the oil becomes brown. However, the thing that has the most influence is the presence of hydrocarbons which make the color intensity of the oil darker (Mulyati *et al*., 2015).

The color tends to be darker in cooking oil used at certain temperatures and heating times due to the formation of oxidation products and pigment formation (Kittipongpittaya *et al*., 2020; Nayak *et al*., 2016). The decomposition of peroxide due to heat will form aldehyde and carbonyl compounds which contribute to the blackish brown color of cooking oil (Burhan *et al*., 2018). The oxidation process that occurs during frying also causes damage to carotenoid, phospholipid, tocopherol and chlorophyll pigments contained in cooking oil and fried foods so that the color becomes darker (Karoui *et al*., 2011; Nurdiani *et al*., 2021; Sobhani *et al*. (2018); Suroso, 2013). Further hydroperoxide oxidation also produces degradation products with three main types, namely breakdown into alcohol, aldehyde, acid, and hydrocarbon, which also contributes to the color change of cooking oil which is darker and changes in flavor, dehydration forms ketones, or free radicals in the form of dimers, trimers, alcohols, and hydrocarbons (Aminah, 2010).

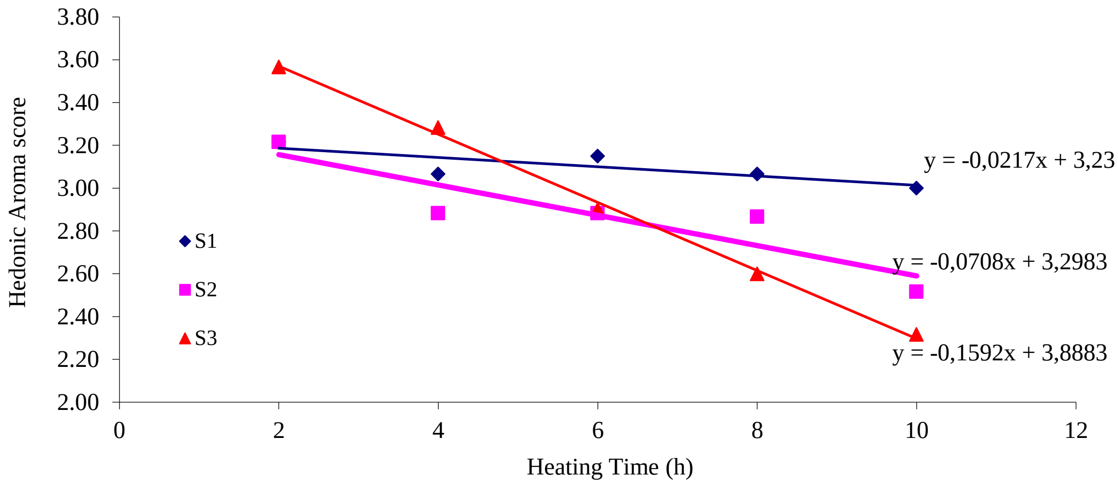

Figure 9. Effect of heating temperature and heating duration on the hedonic aroma of RPO after heating

3.6. Aroma Hedonic Test

Panelists rated the aroma of RPO after heating between 2.3 (strongly dislike) and 3.4 (dislike). As heating temperature and duration increased, panelists showed less preference for the oil aroma due to the development of burnt and rancid odors from oxidation (Ketaren, 2012). The hedonic aroma test on RPO is a test that shows the panelist responses to the aroma of RPO products. The observation results of each hedonic aroma treatment after heating RPO ranged from 2.3 (very dislike) to 3.4 (less like). The heating temperature and heating duration caused the panelists to dislike to dislike the aroma of RPO after heating. In Figure 8, the results of the hedonic aroma test of RPO after heating experienced a decrease in the panelist preference level at heating at 180°C and 220°C with heating durations of 6 h, 8 h and 10 h. This proves that the higher the temperature and heating duration of RPO can cause the aroma of the oil to become unpleasant (burnt smell) and will even cause a rancid smell. The oil becomes unpleasant (burnt smell) or becomes rancid due to the oxidation reaction in the oil. Oxidation reactions can occur at room temperature or during heating at high temperatures, causing the oil to smell. Burnt or even rancid odors are caused by the breakdown of hydroperoxides into compounds with shorter carbon chains due to higher energy radiation, heat energy, catalysts, metals or enzymes. These compounds with shorter C atom chains are fatty acids, aldehydes, ketones which are volatile and cause burnt or even rancid odors in oils and fats (Ketaren, 2012).

3.7. Color Hedonic Test

The color preference of RPO after heating ranged from 2.5 (dislike) to 3.8 (slightly dislike). Higher temperatures and longer heating durations negatively impacted panelist preferences due to the oil darkening, which was likely the result of carotenoid degradation and the formation of oxidation products (Andarwulan *et al*., 1997). Figure 10 shows the results of the hedonic test of the color of RPO after heating, which experienced a decrease in the preference level of panelists at heating at 180°C and 220°C with a heating duration of 8 hours and 10 hours. This shows that high temperatures and heating duration have an effect on the panelist preferences for the color of RPO. The color scoring of palm oil after heating is reddish brown to brown. The dark color in oil is caused by the oxidation of antioxidants (tocopherol) and beta carotene (Siti *et al*., 2001). Furthermore, the formation of peroxides in unsaturated bonds which then decompose peroxides into carbonyl compounds and in some carbonyls polymerization is formed and this causes the oil to become dark in color. The color increases with the longer the heating.

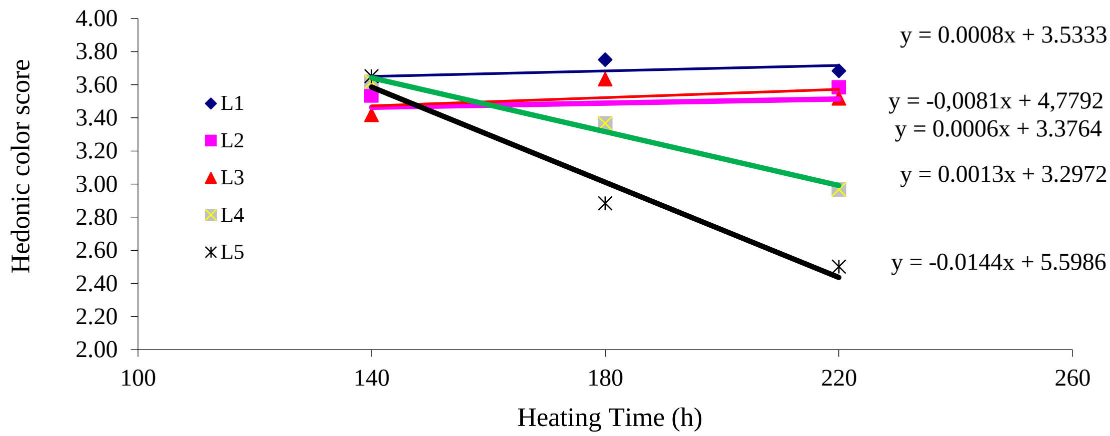

Figure 10. Effect of heating temperature and heating duration on the hedonic color of RPO after heating

The higher the heating temperature, the more peroxide compounds are formed so that the color of the oil becomes darker (Andarwulan *et al*. 1997). In addition, during heating, the volatile compounds contained in RPO will evaporate and cause the color of the oil to change (Putra, 2021). The color tends to be darker in oil used at high temperatures due to the formation of oxidation products and the formation of pigments due to the Maillard reaction (Kittipongpittaya *et al*., 2020; Nayak *et al*., 2016). The oxidation process that occurs during heating also causes damage to the carotenoid and chlorophyll pigments contained in the oil (Karoui *et al*., 2011; Nurdiani *et al*., 2021). This has an impact on the color change of the oil used at a longer temperature and heating time. According to Suroso (2013), the dark color change in cooking oil is caused by changes in tocopherol oxidation and the presence of oil degradation products.

4. CONCLUSIONS

This study demonstrates that prolonged heating and exposure to high temperatures significantly affect both the chemical composition and sensory qualities of RPO. The carotenoid content, which contributes to the nutritional value of oil, particularly its provitamin A activity, undergoes substantial degradation as temperatures exceed 180°C and heating durations extend. Additionally, increased peroxide values and the formation of volatile compounds such as aldehydes and ketones adversely impact the aroma, flavor, and color, making it less desirable for consumption. These results emphasize the need to carefully manage frying temperatures and durations to preserve RPO nutritional benefits and sensory appeal. Further research should explore the development of antioxidant formulations or refining techniques that can enhance the thermal stability of RPO during frying. Investigating the impact of different frying methods and alternative preservation techniques could provide additional strategies to minimize nutrient loss and improve the shelf-life of RPO. Additionally, studies on the health implications of consuming oxidized RPO products are essential to better understand the long-term effects on human health and nutrition

ACKNOWLEDGMENTS:

The authors would like to express their gratitude to the University of Lampung for their financial support and to the laboratory team for their valuable assistance in conducting the experiments. We also extend our thanks to the panelists who participated in the sensory evaluation.

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