

Article

Free Fatty Acid Formation Points in Palm Oil Processing and the Impact on Oil Quality

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Abstract: Background: The level of free fatty acids (FFAs) is an important oil quality index that is consistently measured at mills and refineries to ensure that palm oil is within specification limits. FFAs can accumulate at any point throughout the process, for example, during fresh fruit bunch (FFB) harvesting or during the mill process before sterilisation. Another key contributor to FFA build-up is loose fruit (LF), which is collected following FFB harvesting and is commonly processed together with FFB into crude palm oil (CPO) at the mill. The aim of this study was to identify pivotal points of FFA formation during the process of crude palm oil production. Results: The present study shows that the highest FFA accumulation occurred during the conveying process at the mill before sterilisation due to significant fruit damage. The rapid formation of FFA occurred during the first 15 min of oil palm fruit bruising. A minimum temperature of 60 °C for one hour was needed to deactivate the lipase activity, which is responsible for FFA formation. Blending high-FFA CPO with standard CPO affected indices of palm oil quality, such as the deteriorated peroxide value (PV) and anisidine value (AV), and particularly worsened the bleachability index (DOBI). Conclusions: This study suggests that the conveyor system in the mill could be the prime area to focus on in terms of FFA reduction, along with minimising bruising events. In addition, loose fruits (LF) with high FFA content should be processed separately from FFB, and high-FFA CPO derived from LF should not be mixed with standard CPO.

Keywords: crude palm oil; free fatty acids; loose fruits; lipase activity; deterioration of bleachability index; peroxide value; anisidine value



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1. Introduction

Palm oil is produced from oil palm fruits, *Elaeis guineensis* Jaq., and the extracted oil is known as crude palm oil (CPO) [1]. The fresh fruit bunch (FFB) process line from the estate to the mill steriliser includes several handling steps. Each handling step incurs FFB bruising and contributes to the accumulation of free fatty acids (FFAs). Commonly, loose fruits (LFs) are collected separately from FFBs and brought to the mill for processing soon after the harvesting rounds [2]. LFs generally contain high oil content and accrue FFAs much faster than FFBs [3] once they have fallen to the ground. Despite this, plantation estates try to collect the LFs, as every 20 loose fruits represent a loss of as much as 0.37–0.92% of the oil extraction rate [4].

CPO quality specifications set by the Palm Oil Refiners Association of Malaysia (PORAM) are commonly used as a standard quality requirement for the trading of CPO between millers and refiners; the FFA level is one of the prominent oil quality specifications and is set at a maximum of 5% [3]. Apart from the FFA level, the peroxide value (PV) and anisidine value (AnV) also determine the oxidation quality of CPO [5], although the FFA level is the main parameter that is measured to determine the acceptance of CPO upon arrival at the refinery. The FFAs in CPO may increase upon prolonged storage in the mill and often contribute to higher refining costs that typically occur in the neutralisation step after the degumming process [6,7].

FFA formation is largely attributed to lipase enzymes, which hydrolyse triacylglycerols (TAGs) to diacylglycerols (DAGs) or monoacylglycerols (MAGs) and FFAs. Lipase enzymes are known to be localised at the outer layer of the oil body structure (i.e., oil sacs) in the palm fruit cell [8]. Upon bruising, the oil sacs containing TAGs break and lipases are released. The active site of the lipases, which is exposed to the TAGs, then catalyses the hydrolysis reaction [9]. Several researchers have claimed that, apart from the endogenous lipases, exogenous lipase, which is produced from microbial sources, may also play a role in FFA accumulation in oil palm fruits [10,11]. Previous studies have reported that pre- and post-harvesting factors, such as pest attacks, the maturity of fruits, handling, and delayed delivery to the mill, are the main causes of increased FFAs in both FFB and LF [10,12].

In this study, the accumulation of FFAs in the FFB was investigated from the initial point of the harvesting of bunches and their handling at the estate and the mill for sterilisation. The temperature and time needed to reduce or halt lipase activity was studied in order to explore the appropriate deactivation parameters for lipase in oil palm fruits. We also examined the way LF from the estates have become the main contributors of high FFAs in palm oil and how it may affect the oil quality if blended with standard CPO. The critical handling points of FFBs that resulted in the highest percentage of FFA increase were identified so that alternative ways of improving the logistics and mill process can be suggested.

2. Methodology

2.1. FFB and LF Sampling at Different Handling Points

The collection of FFB and LF samples was performed at various collection points to determine the FFA accumulation as shown in Figure 1.

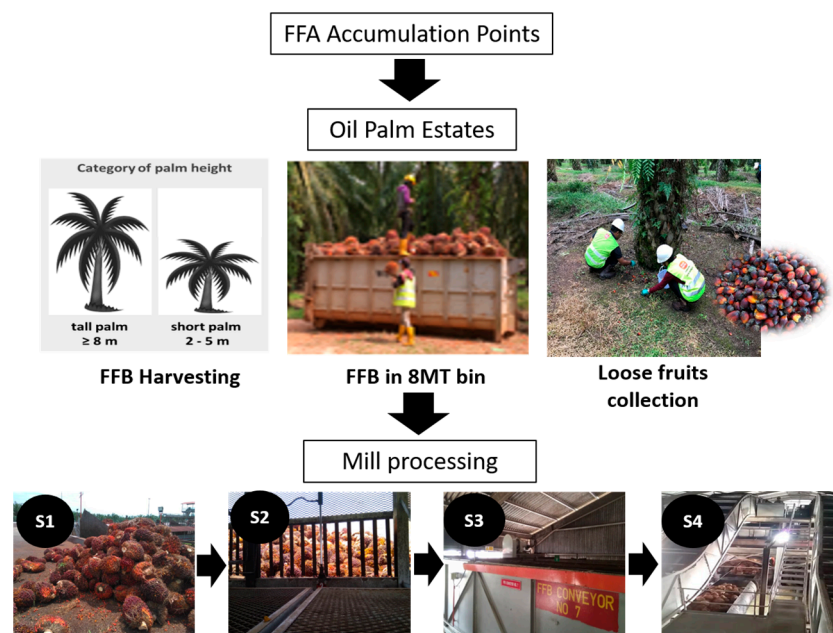


Figure 1. Samples collection points to determine FFA accumulation at the estates and during mill processing.

(a) Collection of FFB and LF upon harvesting at estates

In a trial aimed at studying the effects of height, three bunches were randomly harvested from tall palms (≥ 6 m), and three bunches were randomly harvested from short palms (2–4 m). In all experiments, ripe Tenera bunches with the typical 5–10 empty sockets and LFs were collected from various estates of the Sime Darby Plantation on the day of harvesting. The bunches were transported to the research facility within 2 h of harvesting.

(b) Collection of FFB from the 8-metric ton (MT) bin

Ten oil palm FFBs were collected from the 8-MT where the bunches from the bottom and top layer were marked after being dumped from the mini tractor bin at the estate during a harvesting round. After the bin was emptied at the mill ramp, the marked bunches were collected and individually placed into gunny sacks and sent for sterilisation at the mill. Oil was extracted as described in Section 2.3 and the FFA level was determined as described in Section 2.2.

(c) Collection of FFB during mill processing

The random sampling of ten oil palm FFBs was performed in the ramp area after the emptying of the 8-m bin, as well as at different points on the conveyor belt in the mill. Accordingly, the points were labelled as S1 (the ramp area), S2 (start of the conveyor belt), S3 (end of the conveyor belt), and S4 (after the weighing hopper, i.e., on top of the cage before sterilisation). Oil was extracted as outlined in Section 2.3 and FFA level determined as described in Section 2.2.

2.2. Analysis of FFA

FFA determination was performed by using a rapid FFA analyser (PalmOil Tester, CDR Florence, Italy). A total of 5 µL of palm oil was added to 995 µL of diluent supplied in the kit and mixed well. Subsequently, 100 µL of the mixed solution was added into 900 µL of FFA test reagent, mixed, and incubated in the analyser before reading. Protocols were according to the manufacturer's recommendations.

2.3. Oil Extraction from FFB and LF

All the FFBs collected for the study were individually placed into gunny sacks and brought to the mill facility for sterilisation. Palm oil was extracted from FFBs and LFs as described by Chew et al. [13] using a mechanical press. The oil was kept at 4 °C until further analysis.

2.4. Blending of High-FFA CPO and Standard CPO

Standard CPO was obtained from Kilang Kelapa Sawit Tennamaram and sent for an oil quality analysis. Standard CPO was used to blend with the CPO processed from LFs with three different FFA content categories: 6%, 11%, and 20%. B = The blending of the two oils was conducted in triplicates at 95:5, 80:20, and 70:30 at a final volume of 1 litre with standard CPO as the higher ratio. The blended oil was analysed for FFA content and CPO characterisation was sent to an accredited external lab, BioSynergy Laboratories Sdn Bhd (Table 1), where analysis was performed. The calculated value for FFA and the deterioration of the bleachability index (DOBI) are as follows:

$$\frac{[\text{FFA/DOBI}_{(\text{LF})} \times \text{Volume}_{(\text{LF})}] + [\text{FFA/DOBI}_{(\text{Bunch})} \times \text{Volume}_{(\text{Bunch})}]}{\text{Volume}_{(\text{LF})} + \text{Volume}_{(\text{Bunch})}} \quad (1)$$

Table 1. Oil analysis tests and method used for analysis.

Test Parameter	Unit	Method Used
Free Fatty Acid	%	MPOB P2.5: 2004
DOBI	-	MPOB p2.9: 2004
Moisture and Volatile Matter	%	MPOB p2.1 Part 1: 2004
Impurities	%	MPOB p2.2: 2004
Peroxide Value	meq/kg	MPOB P2.3: 2004
Iron	mg/kg	AOCS Ca 17-01
Copper	mg/kg	AOCS Cd 15-75
Iodine Value	g/100 g	MPOB p3.2: 2004

Table 1. Cont.

Test Parameter	Unit	Method Used
Carotene	ppm	MPOB p2.6: 2004
Triglycerides	%	AOCS Cd 11d-96
Diglycerides	%	AOCS Cd 11d-96
Monoglycerides	%	AOCS Cd 11d-96
E233	-	UV Spectrophotometer
E269	-	UV Spectrophotometer
UV TOTOX	-	By calculation
Inorganic Chloride	mg/kg	UOP 779
Organic Chloride	mg/kg	UOP 779
Total Chloride	mg/kg	By calculation
Anisidine Value	-	MPOB p2.4: 2004
Soap Content	mg/kg	MPOB p2.13: 2004
Phosphorus	mg/kg	AOCS Ca 17-01
Fatty Acid Composition		
C12:0	%	
C14:0	%	
C16:0	%	
C18:0	%	AOAC 996.06
C18:1n9c	%	
C18:2n6c	%	
C20:0	%	
C18:3n3	%	
Solid Fat Content		
N20	%	
N30	%	AOCS Cd 16b-93
N40	%	
N45	%	

2.5. Study of Temperature Effect on Lipase Breakdown

An experiment was conducted to evaluate the effect of temperature and time on lipase breakdown in both unbruised fruitlets and partially bruised fruitlets. Approximately 20–30 kg of ripe bunches was harvested, and the outer layer fruitlets were stripped from the bunches. Unbruised outer layer fruitlets were randomised and separated into three groups. Each group of fruitlets was heated in water baths set at 40, 60, and 80 °C, respectively. Fruitlets were sampled at 30, 60, 90, and 120 min. After heating, half of the fruitlets from each group were bruised and then incubated at room temperature for 30 min. Then, all the bruised and unbruised fruitlets (control) were autoclaved at 120 °C for 90 min. Oil was pressed from the mesocarp and subjected to FFA analysis (Section 2.2).

2.6. Study of Time Effect on FFA Levels in Bruised Fruits

Outer fruitlets were stripped from ripe FFBs and then bruised evenly using a hammer. The bruised fruitlets were incubated for 0.5, 5, 15, 30, 60, 120, 240, 360, 420, 480, 1200, 1320, and 1440 min at room temperature (25 °C) in an open environment. After incubation, the fruitlets were heated at 100 °C for 5 min to inactive the lipases. The oil was then extracted from the fruitlets, as described in Section 2.3, and subjected to FFA analysis (Section 2.1).

2.7. Statistical Analysis

All the results were presented as means of the replicates, and data accuracy was determined using standard deviation. A statistical one-way analysis of variance (ANOVA) with a post hoc Tukey test ($p = 0.05$) between the control and treatment groups was determined using Minitab software, version 20.4.0.0.

3. Results and Discussion

3.1. FFA Accumulation Points

We investigated the key points of FFA accumulation, namely harvesting, crop transfer steps, waiting/transfer time, crop mingling, and mill conveying, followed by sterilisation, in order to determine the relative contribution of these factors. The harvesting of oil palm bunches generally begins when they are 24 months old, and age is strongly correlated with height, which increases by 0.3–0.4 m every year [14]. It has been reported that older palm trees, being taller, have larger FFBs, which, in turn, leads to a higher degree of damage inflicted on the FFBs upon falls from these trees [15]. Contrary to these findings, Figure 2A shows that there was no significant difference in the FFA level of FFBs dropped from both short (2–4 m) and tall (>6 m) palms. No obvious bruised areas were observed on the FFBs collected from either the short or the tall palms, resulting in low FFA levels between 0.28 and 0.34%. The low level of FFAs in FFBs may be attributed to minimum bruising on the surface of the outer layer of fruitlets, as the majority of inner fruitlets were protected from the fall damage. Typically, FFB weight ranges from 3–5 kg after 2 years to over 30 kg after 15 years of planting, where 20–25% of the weight consists of outer fruitlets [16]. In our findings, the bruised outer fruitlets recorded for each FFB accounted for an average of $13.4 \pm 7.1\%$ over bunch weight (internal data), contributing to a dilution effect and the overall low FFA in this experiment.

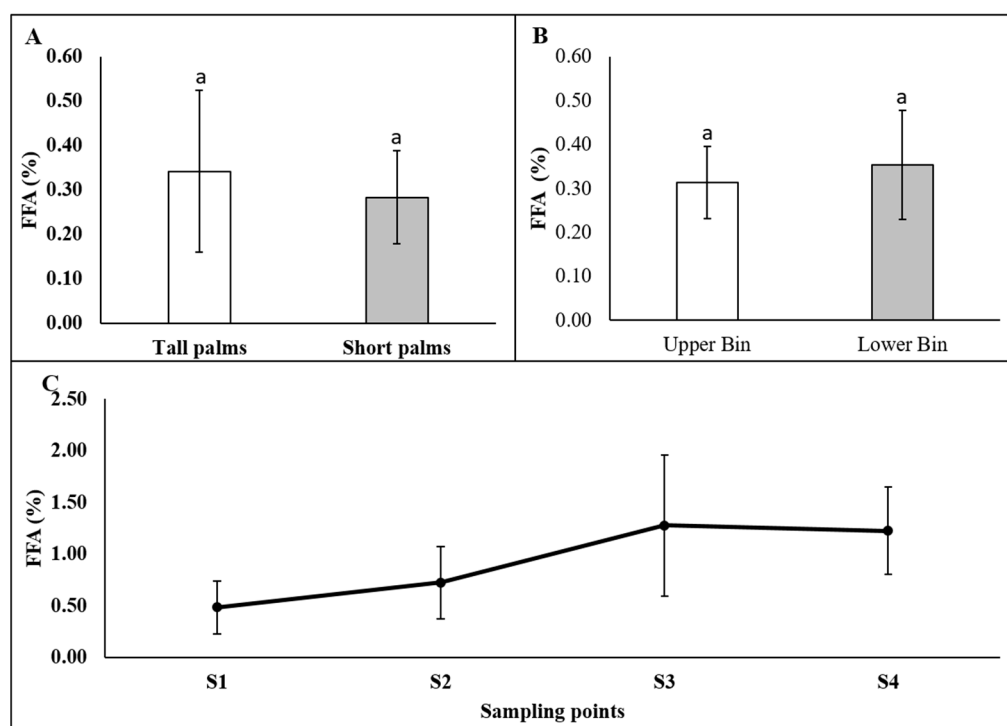


Figure 2. FFA level of bunches harvested from short and tall palms. (A); FFA level of FFBs collected from the upper and lower contents of the 8-m bin (B); FFA level of FFBs collected from S1 (ramp), S2 (start of the mill conveyor), S3 (end of the mill conveyor), and S4 (sterilisation cage) (C). The data are presented as means of the replicates ($n = 10$), and vertical bars indicate standard deviation. Means that do not share a letter were significantly different at $p < 0.05$, according to Tukey's range test.

The handling of FFBs during loading and transport can cause injuries to the FFBs, especially during the loading of FFBs into the truck bin. The degree of injury is higher when the FFB is dropped onto the base of the truck bin directly. Conversely, the drop impact on the FFBs in the upper layer will be lower, as the FFBs in the lower layers act as a cushion to absorb the impact energy [17]. Similar trends were observed in this study, with slightly higher FFA levels observed in FFBs collected from the lower areas (0.35%)

compared to those from the upper areas (0.31%) of the 8-m bin; however, the difference was not statistically significant (Figure 2B). The emptying of the 8-m bin does not occur until the bin is filled to capacity, resulting in a holding time of up to 1 h, which is further delayed during the rainy season.

Once full, the bin is transported to the nearest mill and dumped in the ramp area. FFBs are later channelled into the conveyor system and brought to the sterilisation cage. In this study, the FFA level from the sampling points on the ramp and at the sterilisation bin was investigated. Figure 2C illustrates the range of FFA levels in FFBs taken from different points in the mill. FFBs that were taken from S1 showed the lowest FFA levels at 0.48%. After the FFBs were loaded onto the ramp, more damaged surfaces were observed, as evidenced by the sample collected at S2, and FFA increased to 0.72%. The journey from S2 to the point at the end of the conveyor belt, S3, caused further damage to the FFBs, reflected in an increase of FFA to 1.22%. The final increase in FFA level came at S4, which added a further 0.58%. The results showed that the highest contribution of FFA level came from the conveying process, where the FFBs were moving as a load, which may have caused friction between the bunches and the steel of the conveyor belt. At certain points, the FFBs moved over sharp inclines from which they were dropped to another conveyor belt.

3.2. Effect of Bruising on the FFA Increment Rate

In order to understand the rate of FFA build-up in the oil palm fruits, we conducted a time study on FFA accumulation over time. A rapid FFA increase was observed within the first 15 min after bruising, at a rate of $0.11\% \text{ min}^{-1}$, followed by a gradual increase in FFA level from 30 min to 8 h (480 min) (Figure 3). Similar observations were reported by Chong and Sambanthamurthi [18], where the highest increment in FFA after bruising was observed in the first 15 min. There was no further increase in FFA level after 8 h post-bruising. Another study by Nizam et al. [19] indicated that oil palm fruitlets from the bunches similarly displayed a rapid FFA increase from 0 to 20 h and reached a plateau at 70 h.

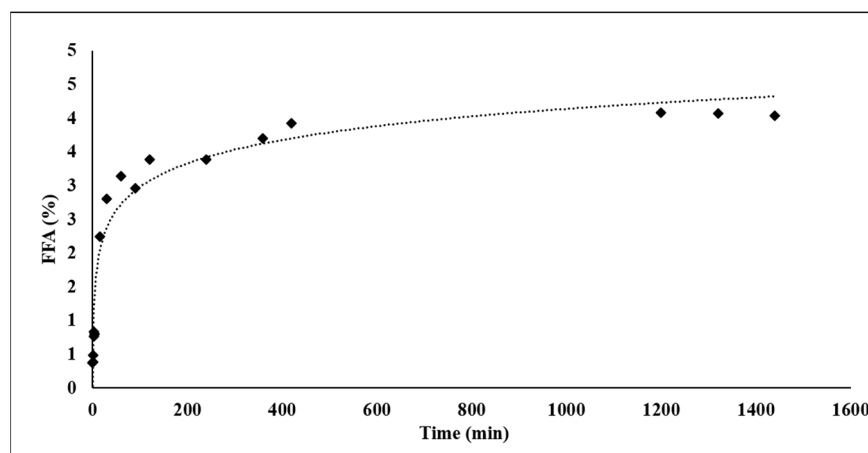


Figure 3. A log exponential line fitted to the FFA level in bruised fruitlets over time.

3.3. Optimum Temperature and Time to Halt Lipase Activity

Lipase activity and the degradation of TAG were extremely rapid—within minutes, it was exposed to the oil. In this experiment, the fruitlets were partially bruised before the temperature treatment to enable the rupture of oil sacs to activate the lipases. Figure 4 shows a downward trend in FFA content when the bruised fruitlets were incubated at 40 °C, 60 °C, and 80 °C over time. Slightly lower FFA contents were observed in bruised fruitlets incubated at 40 °C for 60 min ($6.56 \pm 1.51\%$) than for 30 min ($8.17 \pm 0.58\%$) from the initial FFA of $8.62 \pm 0.29\%$. No significant difference was observed in the FFA content after 60 min of incubation. This indicates that most of the lipases were still active at 40 °C even at longer incubation times of up to 60 min. A reduction of 61.27% in FFA content was observed when

heating the bruised fruitlets at 60 °C for 30 min ($3.16 \pm 1.7\%$), as compared to heating at 40 °C ($8.17 \pm 0.57\%$) for the same amount of time. This demonstrates that lipases were deactivated more effectively at 60 °C than at 40 °C in 30 min. A higher number of lipases may have been deactivated after prolonged heating for 60 min at 60 °C, as it resulted in a low FFA of $0.34 \pm 0.1\%$. The lipases were completely deactivated within 30 min of heating at 80 °C, as low FFA levels were observed at 0.27%. The finding suggests that a holding time of 60 min at 60 °C is sufficient to deactivate lipases in the oil palm fruitlets. However, further experiments are required to validate this process by using FFBs, as they have more complex structures and might require longer heating times and higher temperatures to deactivate lipases in the inner fruitlet layers.

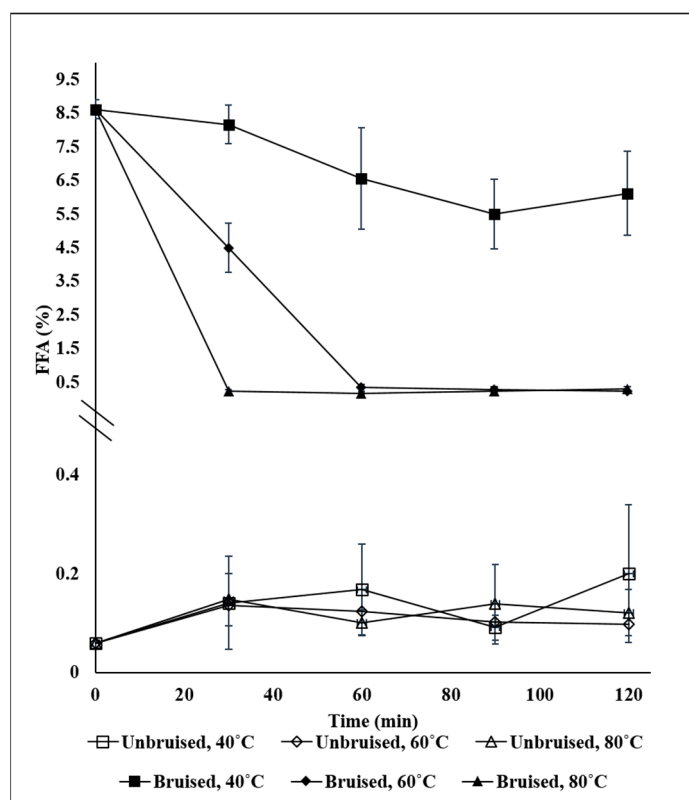


Figure 4. FFA accumulation of bruised and unbruised fruitlets over time. The data are presented as the means of the replicates ($n = 3$), and vertical bars indicate standard deviation.

3.4. FFA Level of LFs Collected from Palms

It is inevitable that LFs are processed along with FFBs at the mills to produce CPO. Often, FFA accumulation in LFs contributes to the high FFAs in the final CPO produced. Oil palm estates are recommended to process LFs on the same day as the FFBs are harvested, but this process is often restricted by labour shortages and logistics issues [20]. Figure 5 shows the increment in FFA level in fresh LFs collected from estates over time. These data could provide an indication of the golden period for LF processing, which is recommended to take place one day after their transport from the estate to the mill. The initial FFA values for the sampled LFs from all five estates were between 1.5% and 4.5%, with the average being 3.3%. The FFAs increased rapidly from Day 2 to Day 6 to 10.3% but slowed down from Day 8 to Day 14, with 12.8%.

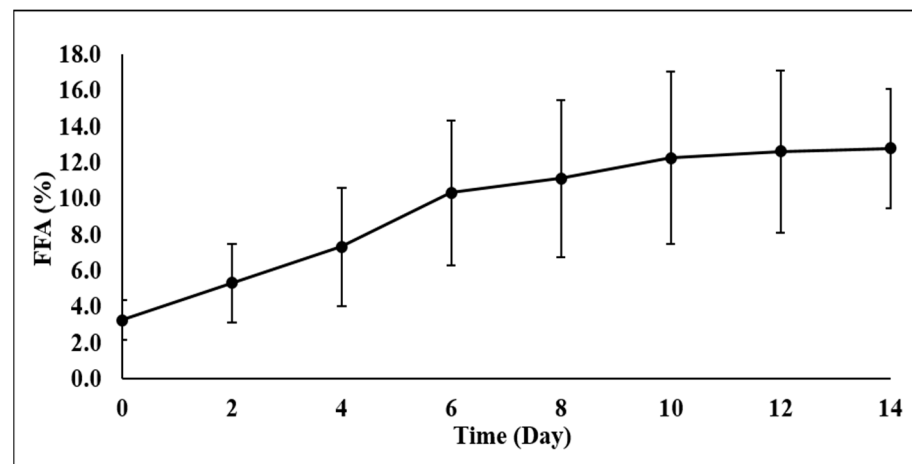


Figure 5. FFA level from LF collected from various estates and its increment over 14 days. The data are presented as the means of the replicates ($n = 5$), and vertical bars indicate standard deviation.

3.5. Characteristics of LF-Extracted CPO

The LFs collected from the estates often contain high levels of FFAs; however, the characteristics of the LF-CPO are not well reported. Table 2 shows the oil quality of the LF oil that was used for blending with standard CPO.

Table 2. Oil characteristics of LF oil with different FFA contents.

Oil Characteristics		LF Oil			Standard Specification
FFA (%)	6	11	20		5 Max
DOBI	3.27	2.01	1.83		2.3 Min
AnV	3.4	7.9	8.5		4 Max
TAG (%)	90.5	78.3	48.5		95 Min
DAG (%)	3.2	2.7	6.3		4 Max
MAG (%)	6.3	19	45.2		NA
M&I (%)	0.18	0.19	0.18		0.15
PV (meq O ₂ /kg)	1.28	0.81	0.72		3 Max
Iron (mg/kg)	0.7	0.1	<0.1		5 Max
Copper (mg/kg)	<0.1	<0.1	<0.1		0.2 Max
IV (I ₂ /100 g)	54.5	54.6	55.0		52–55
Carotene (ppm)	687.2	647.1	676.9		500–700
TOTOX	5.96	9.52	7.04		
Soap Content (mg/kg)	<10	<10	<10		10 Max
Phosphorus (mg/kg)	9.6	2.6	7.2		10 Max

FFA: free fatty acid; DOBI: deterioration of bleaching index; M&I: moisture and solid impurities; PV: peroxide value; AnV: anisidine value; TOTOX: total oxidation; IV: iodine value; TAG: triacylglycerol; DAG: diacylglycerol; MAG: monoacylglycerol.

FFA content, DOBI, moisture, and impurities are essential indicators of CPO quality. In this study, the FFA contents of the LF-CPO were 6%, 11%, and 20% and were named LF-6%, LF-11%, and LF-20%, respectively.

The DOBI values of the three categories were 3.27, 2.01, and 1.83, which indicates a reduction in the DOBI value in accordance with the increasing FFA level. The CPO oxidative stability was examined by determining the level of primary and secondary oxidation products. The PV and AnV values in LF-6% were 1.28 and 3.4, respectively. A higher FFA level corresponded with an increase in the AnV value but not the PV value. Findings by Goudoum et al. [21] showed that higher FFA corresponded with higher PV but other studies [22–24] revealed no correlations. For a better representation of oxidative oil stability, TOTOX was used. The total oxidation (TOTOX) was calculated using the summation of 2PV and AnV. Although TOTOX is not specified to any standards, it is widely

used for quality monitoring [25,26]. The results show that the TOTOX value increased when the FFA level increased. Meanwhile, the results showed that the carotene content in all high-FFA LF-CPO was comparable to the typical carotene range in palm oil between 500 and 700 ppm [27,28].

The TAG in the LF-6% was 90.5%, but when the FFA increased to 11% and 20% in LF-11% and LF-20%, the TAG level decreased to 78.3% and 48.5%. The DAG level of the three LF-CPOs with different FFA ranged from 2.7% to 6.3%. The MAG level in LF-6% was 6.3% but drastically increased to 19% and 45.2% when the FFA was 11% (LF-11%) and 20% (LF-20%). We observed that DAG content in the oil composition was the lowest, as it undergoes rapid hydrolysis into MAG after formation, resulting in a higher MAG content [29]. The DAG and MAG content in CPO was reported to be linked to the formation of glycidyl esters (GEs), a process contaminant generated during the deodorisation step in oil refining [30].

The typical range for the iodine value (IV) in palm oil is between 52 and 55 [27]. The results showed that the IV of all three LF-CPOs with different FFA levels were within the recommended range. Meanwhile, the iron and copper content was also lower than the standard specification for all LF-CPO samples.

3.6. Effect of CPO Blending with High-FFA LF-CPO

High FFAs in CPO, commonly attributed to LF, were reported to affect the standard quality of CPO [31]. In this study, CPO with high FFA content, which was extracted from LFs, showed a decrease in the DOBI but an increase in the AnV value (Table 3). Therefore, a further study to investigate the oil blending between standard CPO and high-FFA CPO extracted from LF was conducted. Different batches of CPO collected from the mill were combined to obtain an average FFA of 2.60% and were used in the blending (Table 3).

Table 3. Oil characteristics of blended LF oil with standard CPO in different ratios.

Oil Characteristics	CPO	CPO + LF-6%			CPO + LF-11%			CPO + LF-20%			Standard CPO
Ratio		95:5	80:20	70:30	95:5	80:20	70:30	95:5	80:20	70:30	Specification
FFA (%)	2.67	2.96	3.43	3.78	3.3	4.77	5.91	3.71	6.45	8.43	5 Max
DOBI	3.09	2.72	2.42	2.23	2.73	2.41	2.22	2.88	2.30	2.00	2.3 Min
AnV	1.8	4.1	5.3	5.5	4.7	6.2	6.6	4.6	5.3	6.0	4 Max
TAG (%)	96.5	94.1	91.8	92.2	93.1	89.2	84.8	92.2	85.6	80.5	95 Min
DAG (%)	2.5	2.9	3.8	3.4	3.3	3.1	5.3	3.3	4.0	4.6	4 Max
MAG (%)	1	3.0	4.4	4.3	3.5	7.6	10.1	4.5	10.4	14.9	NA
M&I (%)	0.1	0.1	0.13	0.1	0.1	0.13	0.1	0.13	0.12	0.14	0.15
PV (meq O ₂ /kg)	0.73	1.67	1.45	3.82	1.34	2.48	3.52	0.95	1.7	3.36	3 Max
Iron (mg/kg)	1.1	0.9	0.4	0.9	0.3	0.3	0.6	1.2	0.9	0.4	5 Max
Copper (mg/kg)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.2 Max
IV (I ₂ /100 g)	52.6	53.9	54.1	54.5	53.2	53	53.7	53.5	52.5	54.1	52–55
Carotene (ppm)	582.4	560.6	537.6	520.7	561.6	523.8	514	549	513.6	523.4	500–700
TOTOX	3.26	7.44	8.2	13.14	7.38	11.16	13.64	6.5	8.7	10.72	
Soap Content (mg/kg)	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	10 Max
Phosphorus (mg/kg)	6.9	7.5	9.3	9.0	7.8	8.0	8.6	7.3	6.8	8	10 Max

Note: LF-6%: loose fruits extracted oil with 6% FFA content; LF-11%: loose fruits extracted oil with 11% FFA content; LF-20%: loose fruits extracted oil with 20% FFA content; FFA: free fatty acid; DOBI: deterioration of bleaching index; M&I: moisture and solid impurities; PV: peroxide value; AnV: anisidine value; TOTOX: total oxidation; IV: iodine value; TAG: triacylglycerol; DAG: diacylglycerol; MAG: monoacylglycerol.

Blending 5% of LF-6% into the CPO slightly increased the final FFA level of blended oil to 2.96%. A higher ratio of LF oil gradually increased the FFA level in the blended oil. The blending of CPO with 20% of LF-6% was still able to meet the specification standards of PORAM, maintaining a final FFA level of below 5% and other characteristics still within the appropriate range, except for the AnV value.

It was observed that by increasing LF oil to 30%, two of the characteristics linked to oil oxidation, DOBI and AnV, exceeded the acceptable range, although the FFA was

only at 3.78%. When the LF-11% oil was used, blended oil was able to maintain an FFA below 5%, with a blending ratio of 5% and 20% LF oil, although DOBI and AnV were unable to meet the PORAM specifications. However, the blended oil exceeded all standard specifications, particularly the FFA level, when 30% of LF-11% oil was used. Similarly, the blending of LF-20% into CPO substantially increased the final FFA level of the blended oil, while 20% and 30% addition exceeded the PORAM specifications. There is some evidence of non-linear effects for DOBI, particularly when a higher ratio of poor-quality LF oil was added into the standard palm oil (Figure 6). The low value of DOBI indicated that the blended oil may need higher bleaching earth during refining, and the effect may lead to a less stable oil that deteriorates faster. A future comprehensive study of the quality parameters and oil stability after mixing CPO extracted from FFB and CPO extracted from loose fruit should be explored.

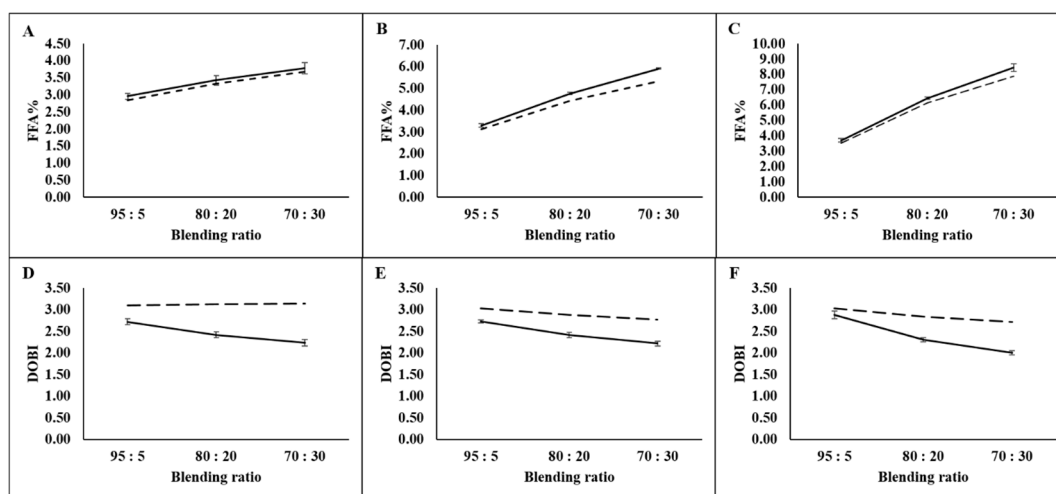


Figure 6. Comparison between calculated (dotted) and actual (solid) FFA level and DOBI value after blending, according to Equation (1). The blending of standard CPO with 6% FFA CPO (A,D); the blending of standard CPO with 11% FFA (B,E); the blending of standard CPO with 20% FFA (C,F); the data are presented as means of the replicates ($n = 3$), and vertical bars indicate standard deviation for actual samples.

The blending of standard CPO with high-FFA LF oil resulted in a reduction in the TAG content in the sample, which coincided with a higher FFA level. In addition, the blending of standard CPO with high-FFA LF oil also showed a deterioration in oil quality, such as worse values of the DOBI, PV, and AnV, which indicated a higher oxidation rate of the oil [32,33]. A similar study was conducted with palm-pressed fibre oil, which contains 5.38–8.26% of FFAs, blended into CPO [34], and a deterioration in blended CPO was found to result in a lower DOBI and higher AnV. Although the FFA level was treated as an indication of the oil quality, our present study has clearly shown that it is equally important to observe other characteristics of the oil to determine its quality, such as the DOBI, AnV, PV, and TOTOX. The mentioned parameters indicate the simplicity of the refining process and the oxidation condition of the crude palm oil. If the values are high, it reduces oxidative stability. Thus, it is not recommended to mix LF oil with standard CPO even at 5% blending, as this may affect the overall oil quality and incur higher refining costs. Similarly, separate LF processing in the mill is highly recommended to prevent a deterioration in oil quality.

4. Summary

At the first impact with the ground, FFBs harvested from both short and tall palms had low FFA levels between 0.24 and 0.38%, respectively. Similarly, minimal FFAs with 0.31% and 0.35% increases were observed in bunches collected from either the top or the bottom of the 8 m bin. An increment of 1.22% in FFAs was observed at the start of the

conveyor belt in the mill due to the use of the front-end loaders, pneumatic gates, and drag lines, directly causing substantial abrasions to the bunches during their transport into the sterilisation cage. Once oil palm fruits were bruised, the FFA level increased rapidly by $0.11\% \text{ min}^{-1}$ within the first 15 min, but plateaued after 6–8 h, which explains why the prevention of bruising fruitlets in the first place is important. High FFA levels in CPO are commonly attributed to LFs, which cause significant changes in oil quality, in terms of, for example, DOBI, peroxide, and anisidine values, even at only a 5% addition to standard CPO. A reduction in handling instances is suggested to prevent mechanical damage and to maintain the quality of the fruit. Furthermore, it is recommended to sterilise the FFBS as soon as they reach the mill. Future mill designs should also take into consideration the type and length of the conveyor system. LFs with high FFA levels should be processed separately from bunches, and if separation is impossible, LFs should be collected and sent to the mill for processing as soon as possible to minimise the rise in FFAs. It may be worthwhile to centralise LF processing at one mill and channel the high-FFA bulk oil to be converted to biodiesel instead.

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