

Effect of Sterilization Time and Temperature Stability on Free Fatty Acid Formation in Crude Palm Oil: Implications for Sterilizer Asset Performance

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ABSTRACT

This study investigated the effect of the sterilization time of Fresh Fruit Bunch (FFB) on the Free Fatty Acid (FFA) content in Crude Palm Oil (CPO). It evaluated its implications for sterilization asset performance. A laboratory-scale experiment was conducted using a manual steam sterilizer heated by a gas stove, resulting in fluctuating sterilization temperatures. Three sterilization durations (30, 45, and 60 min) were tested, each with two replicate groups. Crude oil was extracted using a hydraulic press, and FFA content was determined using alkali titration 0.2 N NaOH and phenolphthalein indicator. The results showed considerable variation in FFA content among treatments. The lowest FFA value (2.50%) was obtained in the 60-min treatment and was the only result that complied with the Indonesian National Standard (SNI 01-2901-2006), which limits FFA content to 5.00%. In contrast, the highest FFA values reached 13.13% and 13.30% in the 45-min and 60-min treatments, respectively. These findings indicate that temperature instability during sterilization had a greater impact on FFA formation than sterilization duration. From an asset management perspective, sterilization equipment is a critical asset whose operational performance directly influences product quality. Therefore, maintaining stable sterilization temperatures is essential for minimizing FFA formation and ensuring consistent CPO quality.

Keywords: Asset Management, Crude Palm Oil, FFB Sterilization, Free Fatty Acid, Temperature Stability,

INTRODUCTION

Oil palm (*Elaeis guineensis* Jacq.) is one of Indonesia's most strategic plantation commodities and plays a crucial role in supporting national economic growth. Indonesia remains the world's largest producer and exporter of crude palm oil (CPO), contributing more than half of the global palm oil supply and generating substantial foreign exchange earnings from the agricultural sector [1],

[2]. CPO serves as a primary raw material for food products, oleochemical industries, cosmetics, and renewable bioenergy, making its quality an important factor affecting downstream industrial performance and market competitiveness [3].

One of the most critical quality parameters of CPO is the Free Fatty Acid (FFA) content. FFA is formed through the hydrolysis of triglycerides by

endogenous lipase enzymes naturally present in oil palm fruits [4], [5]. The hydrolysis process begins immediately after harvesting and accelerates when fruits are mechanically damaged or exposed to unfavorable handling conditions. Elevated FFA levels negatively affect oil quality, reduce extraction efficiency, increase refining costs, and lower the commercial value of CPO in international markets [7], [8]. Therefore, controlling FFA formation is essential for maintaining product quality throughout the palm oil processing chain [10], [11].

MATERIALS AND METHODS

Materials and Equipment

The primary material used in this study was Fresh Fruit Bunches (FFB) of the Tenera oil palm variety (*Elaeis guineensis* Jacq.). The chemicals employed for FFA analysis included 0.2 N sodium hydroxide (NaOH) as the standard titrant solution, 1% phenolphthalein indicator prepared in 95% ethanol, and neutralized 95% ethanol as the solvent. The determination of FFA content followed the alkali titration principle commonly used in crude palm oil quality analysis according to the American Oil Chemists' Society (AOCS) method and previous studies on palm oil quality assessment [4], [7], [8]. The equipment used in this study consisted of: (1) a laboratory-scale manual steam sterilizer made of stainless steel and heated by a gas stove; (2) a manual hydraulic press for oil extraction; (3) standard laboratory titration apparatus including a 50 mL burette, Erlenmeyer flask, and retort stand; and (4) an analytical balance with an accuracy of ± 0.01 g. The manual steam sterilizer was selected to simulate small-scale sterilization conditions where temperature fluctuations are likely to occur due to the absence of an automatic temperature control system [12], [16].

Experimental Design

A Completely Randomized Design (CRD) was employed with three sterilization time treatments: 30 minutes, 45 minutes, and 60 minutes. Each treatment consisted of two experimental groups, resulting in six treatment groups in total. Three titration replications were conducted for each

Sterilization of Fresh Fruit Bunches (FFB) is a critical stage in palm oil processing because its primary function is to inactivate lipase enzymes and prevent excessive hydrolysis reactions that increase FFA content [6], [9], [12]. In addition, sterilization softens the fruit mesocarp, facilitating oil extraction during pressing operations [9]. The effectiveness of this process is strongly influenced by operating conditions, particularly sterilization temperature.

group to improve data reliability and analytical accuracy.

The selected sterilization durations were based on previous studies indicating that heating time significantly influences enzyme inactivation efficiency and FFA formation in palm oil processing [6], [12], [16]. The experiment was designed to evaluate the effects of sterilization duration under laboratory conditions characterized by fluctuating temperatures.

FFB Sterilization Procedure

Sterilization was carried out by steaming the FFB samples using a manual steam sterilizer placed on a gas stove. Approximately 5 g of FFB sample was weighed and subjected to sterilization for 30, 45, or 60 minutes, with timing initiated when the first visible steam emerged from the sterilizer.

Unlike industrial sterilization systems that utilize pressurized steam at controlled temperatures ranging from approximately 120°C to 130°C [17], [18], the laboratory-scale system used in this study relied on direct heating from a gas stove. Consequently, temperature fluctuations occurred during the sterilization process and could not be controlled precisely. These fluctuations constituted an uncontrolled variable that potentially affected the effectiveness of lipase inactivation and the resulting FFA content.

Oil Extraction Process

Following sterilization, the fruits were manually detached from the bunches and mechanically mashed. Oil extraction was then performed using a manual hydraulic press to separate crude oil from the fibrous material and residual water. The extracted oil was subsequently allowed to settle, and the oil phase was separated from water through decantation. The resulting crude palm oil was directly used for FFA analysis.

The extraction process was designed to obtain representative oil samples while minimizing additional processing factors that might influence FFA formation [3], [4].

Determination of Free Fatty Acid Content

FFA content was determined using a modified alkali titration method based on AOCS Ca 5a-40 procedures, which are widely applied in crude palm oil quality evaluation [4], [7], [8].

The analytical procedure was as follows:

1. Five grams of crude palm oil sample (w) were accurately weighed into a 250 mL Erlenmeyer flask.
2. Twenty-five milliliters of neutralized 95% ethanol and three drops of 1% phenolphthalein indicator were added.
3. The mixture was titrated with 0.2 N NaOH solution until a persistent pale pink color appeared and remained for at least 30 seconds.
4. The volume of NaOH consumed (V) was recorded.
5. Each sample was analyzed in triplicate.

The FFA content was calculated as palmitic acid percentage using the following equation:

$$[FFA (\%) = \frac{V \times N \times 25.6}{w \times 10}]$$
where:

- (V) = volume of NaOH consumed (mL);
- (N) = normality of NaOH solution (0.2 N);
- (w) = sample weight (g);
- 25.6 = conversion factor based on the molecular weight of palmitic acid.

The calculated FFA values were compared with the Indonesian National Standard (SNI 01-2901-2006), which specifies a maximum FFA content of 5.00% for crude palm oil [7].

Sterilization Asset Performance Analysis

In addition to evaluating the effect of sterilization duration on FFA content, this study assessed the implications of sterilization equipment performance from an asset management perspective. Sterilization equipment was considered a critical processing asset because its primary function is to maintain process conditions necessary for lipase enzyme inactivation and quality preservation [14], [19], [20].

Asset performance was evaluated descriptively by relating FFA variations among treatments to the effectiveness of the sterilization process. In this study, FFA content was utilized as an Asset Performance Indicator (API), reflecting the ability of the sterilization asset to maintain operational conditions that support product quality [14].

The evaluation focused on three main aspects :

1. Asset Effectiveness – the ability of the sterilization equipment to produce CPO that complies with the SNI quality standard ($FFA \leq 5.00\%$) [7], [14].
2. Asset Performance Stability – the consistency of FFA results obtained under identical sterilization durations [19].
3. Asset Operational Risk – the potential increase in FFA content resulting from
4. temperature instability during sterilization, which may indicate asset performance degradation and increased process variability [20], [21].

Through this approach, the study not only investigated the influence of sterilization duration on FFA formation but also explored the role of sterilization asset performance in maintaining crude palm oil quality.

RESULTS AND DISCUSSION

Free Fatty Acid (FFA) Content at Different Sterilization Times

The results of FFA analysis obtained from six experimental groups subjected to different sterilization durations are presented in Table 1.

Table 1. FFA Content (%) of Crude Palm Oil under Different Sterilization Times

Group	Sterilization Time	P1 (%)	P2 (%)	P3 (%)	Mean (%)	Remarks
1	30 min	5.73	6.12	7.47	6.44	Above SNI
2	30 min	5.98	3.91	4.15	4.68	Near SNI limit
3	45 min	4.30	4.70	5.12	4.70	Near SNI limit
4	45 min	13.90	12.60	13.30	13.13	Far above SNI
5	60 min	13.20	13.90	12.80	13.30	Far above SNI
6	60 min	2.60	2.70	2.40	2.50	Meets SNI

Source: Primary research data, 2024. Maximum FFA limit according to SNI 01-2901-2006 = 5.00%.

The results indicate substantial variation in FFA content among treatment groups. The lowest FFA content (2.50%) was obtained in Group 6, while the highest value (13.30%) was observed in Group 5. Interestingly, groups subjected to identical sterilization durations exhibited markedly different FFA levels, suggesting that factors other than sterilization time influenced the results. This observation indicates that temperature stability during sterilization played a critical role in determining the effectiveness of lipase inactivation and the resulting oil quality [13], [16].

Effect of 30-Minute Sterilization on FFA Content

Groups 1 and 2, which received a sterilization treatment of 30 minutes, produced average FFA contents of 6.44% and 4.68%, respectively. These values were either above or very close to the maximum FFA limit established by SNI 01-2901-2006 [7].

The relatively high FFA levels can be explained by incomplete lipase inactivation during sterilization. Lipase enzymes naturally present in oil palm fruits remain active after harvesting and catalyze the hydrolysis of triglycerides into glycerol and free

fatty acids [5]. Previous studies reported that lipase enzymes are effectively inactivated only when sufficient temperature and heating duration are achieved [12], [15], [16].

The hydrolysis reaction may be expressed as follows:

Triglycerides + H₂O → Diglycerides + Free Fatty Acids

The difference between Group 1 (6.44%) and Group 2 (4.68%), despite having the same sterilization duration, suggests that variations in temperature distribution during the steaming process affected the degree of enzyme inactivation. Group 2 may have experienced a more uniform or higher effective temperature, resulting in lower residual lipase activity and reduced FFA formation.

Effect of 45-Minute Sterilization on FFA Content

A remarkable anomaly was observed in the 45-minute sterilization treatment. Group 3 produced an average FFA content of 4.70%, whereas Group 4 yielded 13.13%, resulting in a difference of 8.43 percentage points despite identical sterilization durations.

This substantial discrepancy cannot be explained solely by sterilization time and strongly suggests the influence of uncontrolled temperature conditions. Excessive temperature fluctuations may have caused thermal disruption of mesocarp cells, leading to the release of intracellular enzymes and increased contact between lipid substrates and catalytic agents. Such conditions accelerate both hydrolytic and oxidative degradation processes, contributing to elevated FFA formation [6], [13].

Previous studies have reported that prolonged exposure to excessive heating may promote oxidative degradation of unsaturated fatty acids, peroxide formation, and a significant increase in FFA content [6]. The absence of automatic temperature regulation in manual sterilization

systems likely contributed to the observed variability.

Effect of 60-Minute Sterilization on FFA Content

The most contrasting results were obtained from the 60-minute sterilization treatment. Group 5 recorded an average FFA content of 13.30%, whereas Group 6 produced only 2.50%, the lowest value among all treatments and the only result meeting the SNI quality standard [7].

The excellent performance of Group 6 suggests that a 60-minute sterilization period, combined with relatively stable temperature conditions, was sufficient to achieve complete lipase inactivation while avoiding excessive thermal degradation. Similar findings have been reported by Sarah et al. [12] and Shehu et al. [16], who demonstrated that adequate thermal treatment effectively suppresses endogenous lipase activity and preserves oil quality.

Conversely, the extremely high FFA content observed in Group 5 further confirms that temperature instability during manual sterilization poses a greater risk to oil quality than sterilization duration itself. Therefore, extending sterilization time alone does not guarantee lower FFA levels unless temperature conditions remain controlled throughout the process.

Temperature Instability and Its Implications for FFA Formation

The use of a manually operated steam sterilizer heated by a gas stove generated dynamic and uncontrollable temperature profiles. Temperature instability may affect FFA formation through two opposing mechanisms.

First, insufficient or uneven heating allows lipase enzymes to remain active, thereby accelerating triglyceride hydrolysis and increasing FFA content [5], [16]. Second, excessive heating or sudden temperature spikes may induce thermal cell disruption and lipid oxidation, which further contribute to FFA accumulation [6], [13].

Industrial sterilization systems generally employ vertical or horizontal sterilizers operating with pressurized steam (1.5–3.0 bar) at temperatures around 130°C [17]. Such systems provide uniform

heat distribution and consistent enzyme inactivation throughout the fruit bunches [18]. The absence of precise temperature and pressure control in the laboratory-scale system used in this study represents a major limitation and explains the significant variability observed among experimental groups.

These findings indicate that temperature stability is a more influential factor than sterilization duration in determining FFA formation under manual sterilization conditions.

Sterilization Asset Performance Analysis and Implications for CPO Quality

The substantial variation in FFA content observed among groups subjected to the same sterilization duration demonstrates that CPO quality is influenced not only by processing parameters but also by the performance of the sterilization asset itself [10], [19].

From an asset management perspective, sterilization equipment functions as a critical asset whose primary role is to maintain stable operating conditions required for lipase inactivation and quality preservation [14], [20]. In this study, FFA content was used as an Asset Performance Indicator (API) because it directly reflects the effectiveness of the sterilization process.

Group 6 produced the lowest FFA content (2.50%) and successfully met the SNI standard, whereas Group 5 generated 13.30% FFA despite receiving the same sterilization treatment. This significant difference indicates substantial variability in asset performance. The inability of the manual sterilization system to maintain consistent temperature conditions increased process variability and reduced product quality reliability [21].

These findings support the concept that asset effectiveness can be evaluated through product quality outcomes. Lower and more consistent FFA values indicate better asset performance, whereas large fluctuations suggest operational instability and increased process risk [14]. Therefore, effective asset management practices—including temperature monitoring, condition-based maintenance, preventive maintenance programs, and operational control—are essential for ensuring

consistent CPO quality and improving overall processing efficiency [14], [19], [20].

Overall, the results demonstrate that sterilization temperature stability is the primary determinant of

FFA formation and that sterilization asset performance plays a direct role in maintaining crude palm oil quality.

CONCLUSION

Based on the experimental results and subsequent analysis, several conclusions can be drawn. First, sterilization time significantly influenced the Free Fatty Acid (FFA) content of crude palm oil (CPO). However, the relationship was not linear because temperature instability during the manual sterilization process exerted a stronger influence on FFA formation than sterilization duration itself. Variations in FFA content observed among groups receiving identical sterilization times indicate that process temperature stability is a critical factor affecting oil quality.

Second, the best treatment was obtained in Group 6, which underwent sterilization for 60 minutes and produced the lowest average FFA content of 2.50%. This was the only treatment that complied with the Indonesian National Standard (SNI 01-2901-2006), which specifies a maximum FFA content of 5.00% for crude palm oil.

Third, insufficient sterilization time may result in incomplete lipase inactivation, allowing enzymatic hydrolysis to continue and increasing FFA formation. Conversely, prolonged heating under unstable temperature

conditions may induce thermal degradation and oxidative reactions that similarly contribute to elevated FFA levels.

Fourth, temperature instability caused by the use of a manually heated steam sterilization system was identified as the primary determinant of the substantial variation in FFA content among treatment groups. This finding demonstrates that effective temperature control is more important than sterilization duration alone in maintaining CPO quality.

Finally, from an asset management perspective, the study confirms that sterilization equipment functions as a critical asset whose operational performance directly affects product quality. The results demonstrate that FFA content can serve as an Asset Performance Indicator (API) for evaluating sterilization effectiveness. Lower and more consistent FFA values indicate better asset performance, whereas high variability reflects operational instability and increased process risk. Therefore, proper asset management practices are essential for ensuring consistent CPO quality and improving processing efficiency.

RECOMMENDATIONS

Based on the findings of this study, several recommendations are proposed.

1. A sterilization duration of 60 minutes is recommended for producing CPO that complies with SNI quality requirements, provided that temperature conditions are maintained

consistently and within the optimal operating range.

2. Future experiments should incorporate continuous temperature monitoring using digital thermometers, thermocouples, or automated temperature control systems to establish a more accurate relationship between

sterilization temperature, heating duration, and FFA formation.

3. Additional quality parameters, such as Deterioration of Bleachability Index (DOBI), moisture content, peroxide value, and impurity content, should be evaluated to provide a more comprehensive assessment of CPO quality.
4. Sterilization equipment should be managed as a critical asset within the palm oil processing system. Preventive maintenance, routine inspection, condition monitoring, and operational performance evaluation should be implemented to ensure stable operating conditions and consistent product quality.
5. Further studies should be conducted using industrial-scale sterilization equipment,

autoclaves, or steam-jacketed systems capable of maintaining precise temperatures within the range of 120–130°C and standardized pressure conditions. Such systems would minimize temperature fluctuations and allow a more accurate evaluation of the effect of sterilization duration on FFA formation.

6. Future research is also recommended to develop quantitative asset performance models that integrate operational parameters, equipment reliability, and product quality indicators. Such an approach would strengthen the application of performance-based asset management in palm oil processing industries and support continuous quality improvement initiatives.

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