

## Integration of Six Sigma and Fuzzy Fmea to Reduce Oil Losses in The Crude Palm Oil (CPO) Processing Industry in Central Kalimantan

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### Keywords

*Six Sigma; Fuzzy FMEA; oil loss; Crude Palm Oil*

### ABSTRACT

*Oil loss during Crude Palm Oil (CPO) processing poses a significant challenge for palm oil mills, leading to decreased productivity, economic losses, and reduced sustainability. This study aims to identify and reduce the causes of oil losses at PT. XYZ in Central Kalimantan using an integrated approach of Six Sigma and Fuzzy Failure Mode and Effect Analysis (FMEA). The research was conducted by analyzing production data from June to August 2024, focusing on oil losses in press cake fiber, empty bunches, and final effluent. The Six Sigma DMAIC method was applied to define, measure, analyze, improve, and control critical factors in the process. The Fuzzy FMEA was used to prioritize potential failures and reduce subjectivity in risk assessment. Results show that final effluent contributed the highest oil loss (37%), followed by press cake fiber and empty bunches. The overall process achieved a sigma level of 4.11, indicating potential for further improvement. Key causes included inconsistent separation processes and inadequate operator monitoring. Suggested improvements involve automation, SOP enforcement, and visual aids through poka-yoke mechanisms. This research provides valuable insights for quality improvement and operational efficiency in the palm oil industry and can be adopted by similar processing plants seeking to reduce losses and increase competitiveness*

## INTRODUCTION

The area of oil palm plantations in Central Kalimantan in 2021 reached 1,872,435 ha with a productivity of 5,542 kg/ha, including smallholder plantations, large state, and private plantations (Directorate General of Plantations, 2022). Based on the 10-year Compound Annual Growth Rate (CAGR) report, Indonesia is the palm oil producer with the largest productivity growth, at 11% (Bokau & Basuki, 2018). Crude palm oil (CPO) production in Central Kalimantan in 2022 was 8,363,763 tons (Directorate of Food Crops Horticulture, 2023). Palm oil is one of Indonesia's leading plantation commodities, contributing greatly to export activities (Hutahaeon et al., 2020). Palm oil mills produce semi-finished products in the form of Palm Kernel Oil (PKO) and Crude Palm Oil (CPO).

The processing of Fresh Fruit Bunches (FFB) into CPO consists of several stages that have the potential to cause oil losses, which negatively impact the economy and environment, such as

decreased yield, increased operational costs, and pollution. Oil loss control is important for production efficiency and sustainability in the palm oil industry. Oil losses also reduce company profitability, although global demand for palm oil remains high due to its widespread use (Semilin et al., 2021).

PT. XYZ is a palm oil processing company that faces challenges in reducing oil losses during the CPO and PKO production process. These losses impact income and result in potential financial losses. Data from July 2024 show oil loss levels at several production stations exceeding the maximum limit set by the company. As stated by Defi et al. (2019), high oil losses reduce production efficiency and cause losses. Therefore, controlling oil losses through approaches such as the Six Sigma method is needed to improve efficiency and production yields.

The Six Sigma method, through the DMAIC (*Define, Measure, Analyze, Improve, and Control*) stages, is used to improve product quality. Its application in the microlens industry in Vietnam improved production efficiency, where modification of the vapor and packaging ratio increased the daily product rate from 69% to 79% and saved \$1,932,367 per year. This shows that Six Sigma is effective in improving operational quality and performance (Wang et al., 2024). In a study by Gupta et al. (2018) regarding the tire manufacturing process in India, the DMAIC method was applied to reduce variation in bead joints, leading to reduced material waste. As a result, the standard deviation decreased from 2.17 to 1.69, while the Cp value increased from 1.65 to 2.95 and the Cpk from 0.94 to 2.66. Based on several previous studies, it is proven that the Six Sigma methodology can solve damage control cases.

The Six Sigma method focuses on statistical analysis and the reduction of variability and defects in processes (Pyzdek & Keller, 2010), but it has limitations in identifying potential failures that are not visible in the data. Therefore, additional approaches such as Failure Mode and Effect Analysis (*FMEA*), a systematic method to identify and analyze potential failure modes in products or processes, are needed (Mandal & Maiti, 2014; Subriadi & Najwa, 2020). The FMEA method helps prevent failures by assessing severity, likelihood of occurrence, and detection capability (Schneider et al., 2024), thereby supporting decision-making to improve environmental performance and regulatory compliance. In addition, FMEA is effective in identifying the root causes of quality problems (Ulfah et al., 2021) and analyzing the impact of failures on product and company functions (Fitriana & Kurniawan, 2020; Ulfah et al., 2021).

To overcome the subjectivity in risk assessment in FMEA, a fuzzy logic approach is used. *Fuzzy* is an effective decision-making method in dealing with uncertainty (Felecia, 2014; Hidayat et al., 2011). The application of Fuzzy FMEA can reduce the subjectivity and uncertainty that often arise in the FMEA risk evaluation process, as well as allow for more flexible and adaptive assessments according to various conditions (Felecia, 2014). Previous research has shown that fuzzy logic can improve decision-making accuracy by considering various factors and providing an objective judgment based on established criteria (Thakkar et al., 2021). Therefore, fuzzy integration with FMEA can increase accuracy and objectivity in identifying the types of waste that have a significant impact and need management priority.

Thus, this study applies the integration of Six Sigma and Fuzzy FMEA to identify and analyze the causes of oil losses and propose improvements to reduce oil losses, thereby improving the quality of Crude Palm Oil (CPO) production in the CPO processing industry in Central Kalimantan.

Previous studies have explored the use of Six Sigma in various industries: Gupta et al. (2018) demonstrated its effectiveness in reducing waste in tire manufacturing in India; Wang et al. (2024) showed efficiency gains in Vietnam's microlens industry using the DMAIC model; and Defi et al. (2019) applied Statistical Process Control to identify oil losses in CPO processing. However, most of

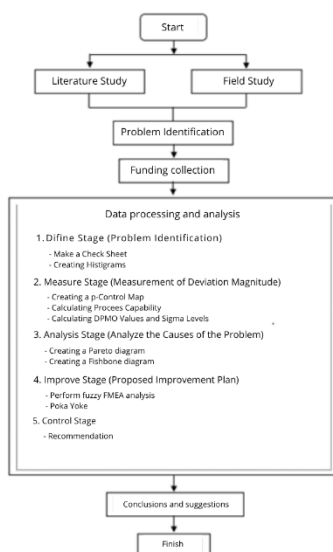
these studies rely solely on statistical or technical process improvements and often overlook the integration of qualitative risk analysis—especially when data ambiguity and subjectivity are involved.

This research addresses that gap by combining Six Sigma DMAIC with Fuzzy Failure Mode and Effect Analysis (*Fuzzy FMEA*) to enhance the identification and prioritization of oil loss causes. The novelty lies in integrating quantitative process control with qualitative risk modeling under uncertainty, making the solution both accurate and adaptive for complex industrial environments.

The objective of this study is to identify dominant sources of oil losses in the CPO production process and to propose data-driven, systematic improvements. The benefits of this research are twofold: it provides practical recommendations for improving process capability and efficiency at PT. XYZ, and it contributes methodologically by advancing the hybrid use of Six Sigma and Fuzzy FMEA in the palm oil industry context.

**METHODS**

This research focuses on controlling oil losses in the Crude Palm Oil (CPO) production process. The study objects include oil loss data from press cake fiber, empty fruit bunches (EFB), and final effluent during June–August 2024. The research process began with a preliminary study comprising field observation and literature review on oil loss issues at PT. XYZ. Subsequently, problems were identified and relevant data were collected. The following stage involved data processing and analysis using the Six Sigma *DMAIC (Define, Measure, Analyze, Improve, Control)* method and *Fuzzy FMEA*. Analysis results were then used to derive conclusions and formulate recommendations. The methodological flowchart is presented in Figure 1.



**Figure 1. Flowchart research methodology**  
Source: Researcher

The population in this study includes all stages of the Crude Palm Oil (CPO) production process that have the potential to cause oil losses. The sample was taken purposively, focusing on three critical loss sources: press cake fiber, empty bunch, and final effluent, based on data from June to August 2024.

Primary data were obtained through direct field observations, interviews with operational staff, and documentation review of production records and oil loss logs at each station. Secondary data was gathered from internal company reports and relevant literature.

The data were analyzed using the DMAIC stages of Six Sigma:

- a) *Define*: Identification of Critical To Quality (CTQ) indicators.
- b) *Measure*: Measurement of oil loss levels and process capability ( $C_p$ , DPMO, Sigma Level);
- c) *Analyze*: Root cause identification using Pareto and fishbone diagrams.
- d) *Improve*: Prioritization of corrective actions using Fuzzy FMEA to evaluate Severity, Occurrence, and Detection.
- e) *Control*: Development of poka-yoke-based control plans to ensure long-term stability.

This combined analytical method enables structured identification of high-impact failures and prioritization of actionable improvements to enhance CPO production efficiency.

## RESULTS AND DISCUSSION

### 1. Problem Identification

This study examines the components of by-products and waste in the palm oil processing process that contribute to oil losses. The three main objects analyzed were press cake fibre, empty bunch, and final effluent, each of which had different characteristics and impacts on total oil losses. Press cake fibre is a solid residue from pressing that still contains oil, an empty bunch is an empty bunch after fruit separation that may still contain residual oil, and final effluent is the final liquid waste of the plant that also contains wasted oil.

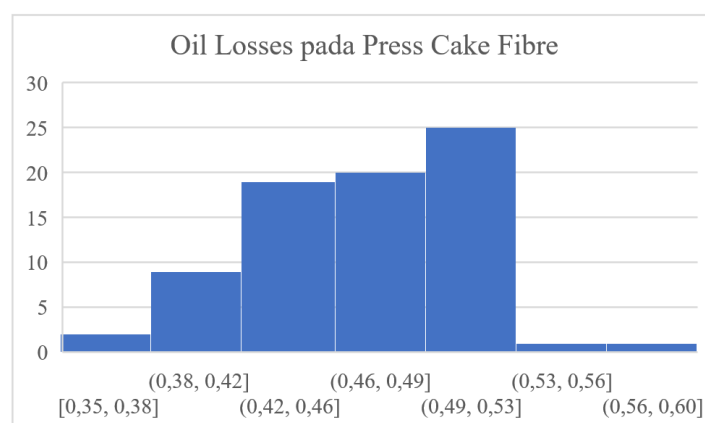
### 2. Define Stage

#### a. Check sheet

Based on the observation results, the total fresh fruit bunches (FFB) processed during the period June – August 2024 reached 69,326,358 kg. Losses incurred in fiber press cakes were recorded at 0.46% or equivalent to 322,035 kg. Meanwhile, empty bunch losses were recorded at 0.38% or as much as 264,626 kg, and at final effluent it was 0.49% or worth 341,796 kg.

#### b. Histogram

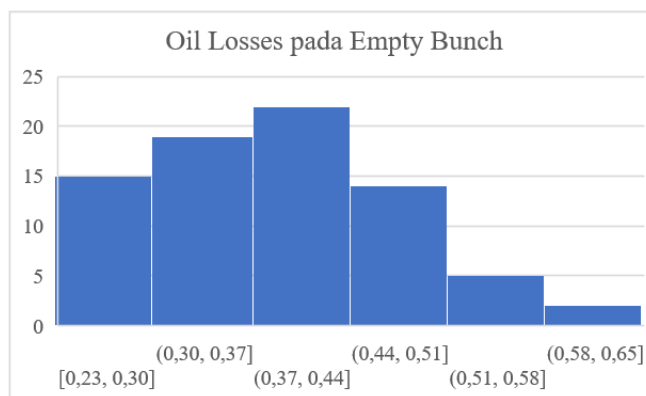
Histograms are used to show the distribution of oil losses at various process points, such as press cake fibre, empty bunch, and final effluent, so that it can help in assessing production efficiency. Histograms at several oil loss points are presented in Figures 1, 2, and 3 below.



**Figure 2. Histogram Analysis**

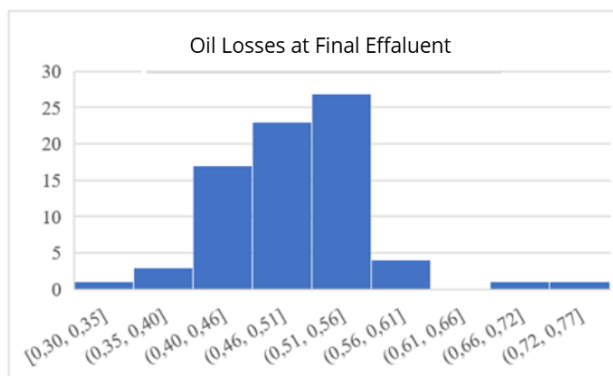
Source: Researcher

In general, the results of histogram analysis of oil loss in press cake fibre (Figure 1) show that most oil losses accumulate in the range of 0.42% to 0.53%, with the highest frequency being in the interval of 0.49% to 0.53%.



**Figure 3. Histogram Analysis**  
Source: Researcher

Based on Figure 2, it can be seen that most of the oil loss in empty bunches is concentrated in the range of 0.23% to 0.44%, with the highest frequency, which is about 22 events, occurring in the range of 0.37% to 0.44%. If the factory's operational standards set a maximum oil loss limit of 0.35%, then this data shows that most of the current processes still produce oil losses that exceed the set limit.



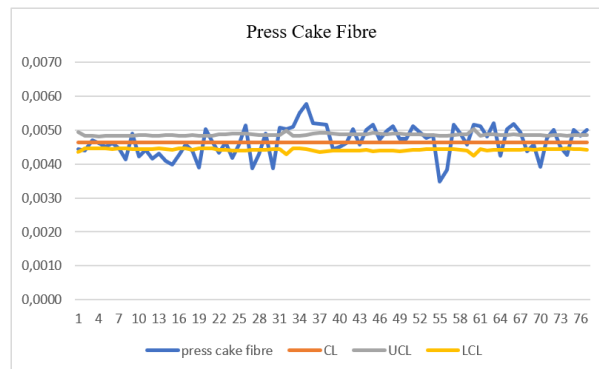
**Figure 4. Histogram Analysis**  
Source: Researcher

Based on the histogram "Oil Losses on Final Effluent", it is known that most of the oil losses in final effluent are concentrated in the range of 0.51% to 0.56%, with the highest frequency reaching about 27 occurrences. This condition shows that the factory standard value of 0.54% is often at the upper limit or even exceeded in the range of oil loss that occurs most frequently.

**3. Measure Stage**

a) P-Control Map

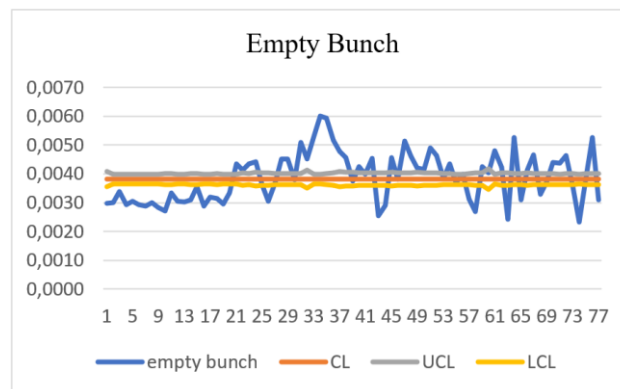
The main purpose of this map is to monitor the consistency and stability of the process, as well as to identify the factors that cause variations that can impact the quality of the products produced. The control map of each oil loss point is presented in Figure 4, 5, and 6.



**Figure 5. P-type Control Map**

Source: Researcher

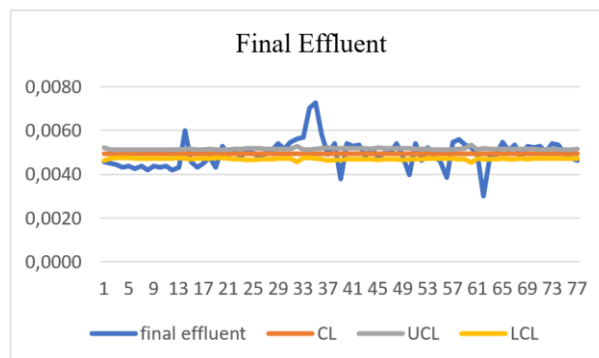
The P-type control map used to monitor the proportion of defects in the press cake fibre (Figure 4) shows that the process is in a statistically uncontrollable state. This is shown by several data points that exceed the control limit (UCL and LCL), such as at the 34th, 35th, and 54th points, which indicate systematic variation due to special causes in the production process.



**Figure 6. P-type Control Map**

Source: Researcher

The P-type control map of the empty bunch shows that the process is statistically uncontrollable, characterized by many observation points beyond the upper (UCL) and lower (LCL) control limits. This uncontrollability was seen consistent over the observation period, with significant deviations at the 3rd, 10th, 20th, 29–37th, 43rd, 49th, 52nd, 60th, 66th, and 70th observation points. This pattern shows the dominance of special causes that sustainably affects the variation in the proportion of defects in the empty bunch.



**Figure 7. P-type Control Map**

Source: Researcher

Analysis of the control map P against Final Effluent shows that the process of separating oil from effluent is in a statistically uncontrolled state. This is demonstrated by the large number of data points that transcend the UCL and LCL, with significant deviations repeating in observations 14, 30–36, 40, 48, 59, and 62. This pattern indicates the presence of systemic special causes and consistently affects the stability and final quality of the effluent.

b) DPMO and Sigma Level

According to Pyzdek (2010), DPMO (Defects Per Million Opportunities) is a metric used to assess the quality of the process by calculating the number of defects per million opportunities, thus providing an overview of the effectiveness of the process and the potential defects that occur. Meanwhile, the Sigma Level indicates a process's ability to produce high-quality products with a low defect rate. The DPMO value and its conversion to sigma level are shown in the Table.

**Tabel 1. DPMO and Sigma Level**

Treatment	Calculation Results
Amount of FFB produced (kg)	69.326.358
Total oil losses (in kg)	928.457
Proportion of oil losses	0,01339256
Number of CTQs (source losses)	3
Defect Per Opportunity (DPO)	0,004464
Defect Per Million Opportunity (DPMO)	4.464,185
Convert DPMO values to sigma levels	4,114785

Source: Researcher

The sigma level of table 1 in oil loss management in palm oil mills reflects relatively good process capabilities, although there is still considerable potential for further improvement.

c) Process Capability

Process capability is an important parameter used to evaluate the extent to which a process is able to consistently produce outputs that are within the limits of predetermined specifications (Thomas Pyzdek (2010)). The calculation of the process capability index value is presented in the Table below.

**Tabel 2. Process Capability**

Treatment	Calculation Results		
	Press cake fiber	Empty bunch	Final effluent
Average of lost proportion	0,0047	0,0039	0,0050
Standard deviation	0,000432926	0,000846228	0,000629858
Upper control limit	0,005971152	0,005643684	0,006840743
Lower control limit	0,003373597	0,001332186	0,003061595
Capability process	1	0,849160031	1

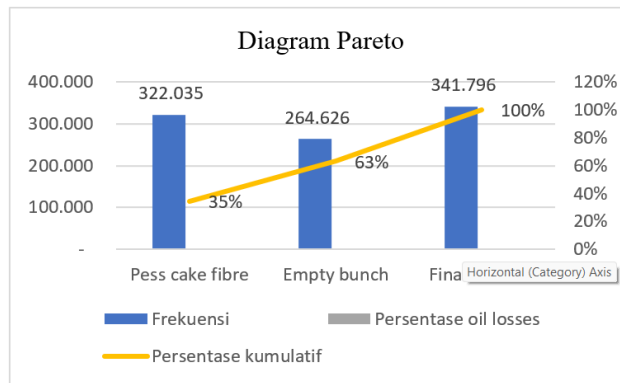
Source: Researcher

The process capability data shows that the oil losses in the Press Cake Fibre and Final Effluent have met the minimum standard ( $C_p = 1$ ), while the Empty Bunch is still below the standard ( $C_p = 0.8491$ ), so it requires technical improvements to improve efficiency and reduce oil losses.

**4. Analyze Stage**

a. Pareto Diagram

A Pareto chart is a quality management tool used to identify and prioritize the cause of a problem based on its contribution level, by presenting the data in a sequential bar graph accompanied by a cumulative curve as an indicator of total contribution.

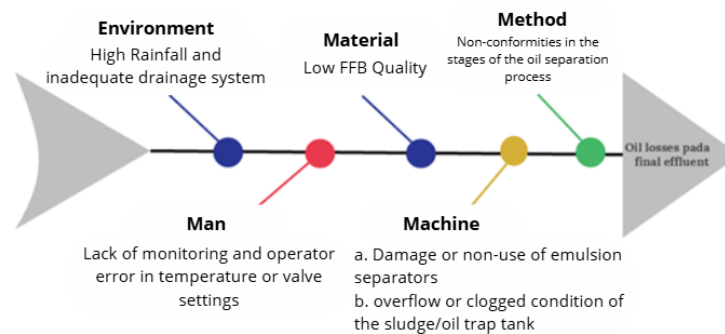


**Figure 8. Pareto Diagram**  
Source: Researcher

Based on Figure 8 above, Final Effluent is the main cause of oil loss with the highest contribution of 341,796 kg. This was followed by Press Cake Fibre (322,035 kg) and Empty Bunch (264,626 kg), which cumulatively accounted for 35% and 63% of total oil losses. Therefore, the priority of reducing oil losses should be focused on the management of Final Effluent to achieve significant increases in efficiency and productivity.

b. Fishbone diagram

The final effluent diagram is presented in Figure 9 below.



**Figure 9. Fishbone Diagram**  
Source: Researcher

**5. Improve Stage**

a) Fuzzy FMEA

In determining the necessary corrective actions, it is necessary to conduct a risk analysis of the various causes of failures that occur. This analysis was carried out using the Fuzzy Failure Mode and Effect Analysis (Fuzzy FMEA) method, which is a development of the conventional FMEA method. Fuzzy FMEA integrates fuzzy logic to address uncertainty and subjectivity in the assessment of risk parameters, such as severity, occurrence, and detection capabilities.

The following table shows the results of Fuzzy FMEA analysis of various failure modes that contribute to the occurrence of oil losses in the final effluent. Each cause is evaluated based on severity, likelihood of occurrence, and detectability, and then classified into risk categories to determine treatment priorities.

**Tabel 3. Fuzzy FMEA**

No	Failure Mode	S	O	D	Fuzzy FMEA	Category
1	Lack of monitoring & operator error in temperature/valve regulation	7	6	6	238	Very High
2	High rainfall & inadequate drainage system	6	7	5	238	Very High
3	Low FFB quality	6	5	6	158,67	High
4	Emulsion separator is damaged/not used	8	6	5	238	Very High
5	Tangki sludge/oil trap overflow/tersumbat	8	7	4	121,33	Moderate
6	Inconsistencies in the stages of the oil separation process	9	6	5	238	Very High

Source: Researcher

b) Poka Yoke

Proposed table of poka yoke implementations for each failure mode.

**Tabel 4. Poka Yoke**

No	Failure Mode	Proposed Implementation of Poka Yoke
1	Lack of monitoring & operator error in temperature/valve regulation	The application of an automatic temperature sensor that has been calibrated accompanied by an alarm system, as well as the installation of a locking mechanism on the valve to ensure that operation can only be carried out in accordance with standard operating procedures (SOPs)
2	High rainfall & inadequate drainage system	The use of automatic water level detectors equipped with warning alarms when there is an increase in rainfall and potential runoff, as well as the addition of bypass pipelines as a measure to handle emergency conditions
3	Low FFB quality	The application of an automatic sorting system based on color and weight sensors aims to identify and separate unsuitable fruits, such as raw or rotten fruit, before entering the next stage of the process
4	Emulsion separator is damaged/not used	The implementation of a functional interlock system ensures that the separator device is in an active state before the entire process can be operated, as well as the addition of a visual indicator in the form of a light as a marker of the operational status of the tool
5	Tangki sludge/oil trap overflow/tersumbat	Utilization of automatic sludge level sensors equipped with warning alarms against potential spills, as well as the implementation of a structured cleaning schedule based on specific time intervals or accumulated volumes
6	Inconsistencies in the stages of the oil separation process	The application of flow and temperature sensors integrated with the interlock system to ensure that each stage of the process runs according to the parameters, as well as the provision of visual guidance as an operational reference for operators

**6. Control Stage**

Based on Table 5 which contains the proposed application of the Poka Yoke method, the next control stage is prepared to ensure that the implementation of the system can run optimally in preventing process failures and minimizing potential oil losses. The control plan table is presented in Table 5.

**Table 5 Control Plan Based on Poka Yoke Proposal.**

No	Failure Mode	Control Plan
1	Lack of monitoring and operator error in temperature/valve settings	<ul style="list-style-type: none"> <li>a. Routine calibration of temperature sensors and alarms is carried out on a weekly or monthly basis to maintain accuracy.</li> <li>b. Checking of alarm records and valve operation history is carried out by the supervisor as an operational control.</li> <li>c. The implementation of a daily checklist ensures valve operation only through a authorized system.</li> <li>d. Compliance audits of SOPs are conducted periodically by the QA team to ensure consistent implementation.</li> </ul>
2	High rainfall & inadequate drainage system	<ul style="list-style-type: none"> <li>a. Visual inspection of drainage systems and bypass pipes is carried out before the rainy season.</li> <li>b. Regular maintenance of drainage is scheduled every month.</li> <li>c. Alarm activation is recorded in the event log as documentation of the incident.</li> </ul>
3	Low FFB quality	<ul style="list-style-type: none"> <li>a). The results of the FFB sorting are documented and checked daily by the receiving officer.</li> <li>b). Unsuitable fruit data per <i>batch</i> is reported as the basis for evaluating the performance of the supplier's plantation.</li> <li>c). The Quality Control Unit conducts weekly verification of the performance of the sorting equipment.</li> </ul>
4	Emulsion separator is damaged/not used	<ul style="list-style-type: none"> <li>a). The status of the separator device is verified through a visual indicator before the operational process begins.</li> <li>b). The operator fills out a daily checklist to record the operational condition of the separator device.</li> <li>c). Technicians conduct weekly inspections of the <i>function of the interlock</i> system.</li> <li>d). Tool downtime and repair response are documented as part of performance control.</li> </ul>
5	Tangki sludge/oil trap overflow/tersumbat	<ul style="list-style-type: none"> <li>a). Sludge level sensor alarm is checked every shift change.</li> <li>b). The tank cleaning schedule is compiled based on the historical data of the sludge volume from the sensor.</li> <li>c). Inspection of sludge and <i>oil trap channels</i> is carried out on a weekly basis using a checklist.</li> <li>d). The operator reports the daily sludge level anomaly to the technician for follow-up</li> </ul>
6	Inconsistencies in the stages of the oil separation process	<ul style="list-style-type: none"> <li>a). The temperature and flow of the process are monitored in real time.</li> <li>b). Each stage of the process is audited based on the visual parameters and alarm system.</li> <li>c). Visual guides are installed in the work area to support operator compliance with procedures.</li> <li>d). QC team verifies standard parameters through daily shift reports.</li> </ul>

Source: Researcher

## CONCLUSION

Three Critical-to-Quality (CTQ) factors contribute to oil losses in the CPO production process, namely press cake fibre, empty fruit bunches (EFB), and final effluent, with final effluent being the largest contributor at 341,796 kg (37%). Although empty bunches have the smallest frequency of losses (29%), their process capability remains substandard with a Cp value of 0.84. The overall process sigma level of 4.11 indicates performance at the Indonesian industry average but still below the global standard. The main causes of oil losses in the final effluent are inconsistencies in the oil separation process, damaged or unused emulsion separation devices, and insufficient operator monitoring. To address these issues, recommended improvements focus on enhancing automation

and sensory systems, enforcing standard operating procedures (SOPs), and providing visual aids and additional safety systems to minimize operator errors, detect abnormal conditions early, and ensure greater efficiency in palm oil production. For future research, it is suggested to incorporate real-time digital monitoring systems to complement statistical controls and improve data accuracy and responsiveness. Additionally, including cost-benefit analysis for each proposed improvement would strengthen decision-making, and validating this integrated Six Sigma–Fuzzy FMEA methodology across CPO factories of different operational scales would further support its generalizability and refinement.

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