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Improving Crude Palm Oil Quality in Storage Tanks through PDCA-Based Control of Free Fatty Acids and Moisture Content

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ABSTRACT

Maintaining CPO quality during storage is essential because elevated FFA and MC levels can reduce product quality, storage stability, and market value. This study investigates the levels of Free Fatty Acids (FFA) and Moisture Content (MC) in storage tanks and their impact on CPO quality using the PDCA framework supported by p-control charts and Fishbone Diagram analysis. The study aims to identify the factors affecting CPO quality and to formulate appropriate improvement strategies. Data on FFA and MC were obtained from the monthly laboratory reports of the mill and analyzed using p-control charts and Fishbone Diagrams. The results showed that 54 FFA samples and 71 MC samples exceeded the company's established quality standards, indicating that moisture content was the dominant quality issue. The p-control chart analysis revealed that the storage process was statistically out of control, reflecting significant process variation during storage operations. Furthermore, the Fishbone Diagram identified several contributing factors related to human, material, machine, and method aspects, including operator inattentiveness, inadequate handling of Fresh Fruit Bunches, improper sorting processes, insufficient equipment maintenance, and suboptimal vacuum dryer pressure control procedures. Several corrective actions were proposed, including strengthening operator supervision, implementing a FIFO system for FFB handling, establishing clearer quality standards, enhancing equipment maintenance practices, and optimizing vacuum dryer operating procedures. The proposed corrective actions are expected to reduce non-conforming FFA and MC samples, improve process stability, and strengthen compliance with established quality standards.
Keyword: *Crude Palm Oil (CPO), Fishbone Diagram, Free Fatty Acid (FFA), PDCA, Quality Control*

ABSTRAK

Menjaga kualitas CPO selama penyimpanan sangat penting karena peningkatan kadar asam lemak bebas (ALB) dan kadar air dapat menurunkan mutu, stabilitas penyimpanan, dan nilai ekonomi produk. Penelitian ini mengkaji tingkat ALB dan kadar air pada tangki penyimpanan serta dampaknya terhadap kualitas CPO menggunakan kerangka kerja PDCA yang didukung peta kendali p dan Diagram Fishbone. Tujuannya adalah mengidentifikasi faktor-faktor yang memengaruhi kualitas CPO dan merumuskan strategi perbaikan yang tepat. Data diperoleh dari laporan laboratorium bulanan pabrik. Hasil menunjukkan terdapat 54 sampel ALB dan 71 sampel kadar air yang melebihi standar mutu perusahaan, sehingga kadar air menjadi masalah yang paling dominan. Peta kendali p menunjukkan bahwa proses penyimpanan tidak terkendali secara statistik, yang mencerminkan variasi proses yang signifikan. Diagram Fishbone mengidentifikasi faktor penyebab dari aspek manusia, material, mesin, dan metode, yaitu kurangnya ketelitian operator, penanganan Tandan Buah Segar (TBS) yang belum optimal, sortasi yang kurang tepat, pemeliharaan peralatan yang kurang memadai, serta pengendalian tekanan *vacuum dryer* yang belum optimal. Perbaikan yang diusulkan meliputi

peningkatan pengawasan operator, penerapan sistem *First In First Out* (FIFO) pada penanganan TBS, penetapan standar kualitas yang lebih jelas, peningkatan pemeliharaan peralatan, dan optimalisasi pengoperasian vacuum dryer. Implementasi perbaikan ini diharapkan menurunkan kadar ALB dan kadar air serta meningkatkan kesesuaian produk terhadap standar mutu. Penelitian ini berkontribusi secara praktis pada perbaikan kualitas berkelanjutan di industri kelapa sawit.
Keyword: Asam Lemak Bebas, Crude Palm Oil (CPO), Fishbone Diagram, Pengendalian Kualitas, PDCA

1. Introduction

Indonesia's agricultural sector plays a significant role in supporting national economic growth, particularly through the palm oil industry, which has become one of the country's major export-oriented sectors. Agricultural productivity largely depends on the availability and effective management of key production resources, including land, labour, and capital. In recent years, the Indonesian palm oil industry has faced increasingly dynamic market competition, reflected in fluctuating commodity prices influenced by global demand, international trade policies, and evolving quality standards. Nevertheless, palm oil continues to be one of Indonesia's leading export commodities, contributing substantially to national export revenues. The prospects of Indonesian palm oil remain highly promising due to increasing global demand, its extensive utilization across various industries such as food processing, cosmetics, and biodiesel production, as well as continuous growth in the global population and economy. Moreover, Indonesia continues to maintain its position as the world's largest palm oil producer, accounting for approximately half of global production.

Oil palm is a perennial tropical plantation crop with high economic value and extensive industrial applications. Crude Palm Oil (CPO) is derived from the mesocarp of oil palm fruit through an extraction process without further refining treatment. As one of the most widely produced vegetable oils worldwide, palm oil is extensively utilized in both crude and refined forms, particularly within the food processing industry. Commercial CPO production is generally conducted on a large scale through wet extraction processes using Fresh Fruit Bunches (FFB) harvested from oil palm plantations [1]. Chemically, palm oil contains a relatively balanced composition of saturated and unsaturated fatty acids in an approximate ratio of 50:50, which differentiates it from most vegetable oils [2]. In addition to triglycerides, which constitute the major component of the oil, CPO also contains free fatty acids, monoglycerides, diglycerides, phosphoglycerates, vitamins, minerals, and minor constituents that influence its physicochemical properties. The quality and economic value of palm oil are closely associated with its fatty acid characteristics, underscoring the importance of effective quality management practices aimed at controlling Free Fatty Acid (FFA) levels throughout processing and storage operations [3].

The quality of Crude Palm Oil (CPO) is a critical factor influencing the competitiveness and operational performance of Palm Oil Mills (POM). High-quality CPO is generally characterized by its reddish-orange appearance, low moisture and impurity content, high storage stability, ease of refining, and minimal hydrolysis reactions that contribute to the formation of Free Fatty Acids (FFA). Therefore, maintaining product quality throughout processing and storage stages is essential. The increasing emphasis on sustainability certification in the palm oil industry underscores the need for consistent quality management practices, including effective monitoring and control of key quality parameters to ensure compliance with industry standards and market requirements [4]. The quality of CPO is critically influenced by parameters such as Free Fatty Acid (FFA), moisture content, and impurities, which directly affect its stability, shelf life, and market value [5]. In industrial operations, storage tanks serve as vital facilities for storing raw materials and processed products prior to distribution or further processing activities. The design and configuration of storage tanks vary depending on industrial requirements, operational capacity, and product characteristics.

Among the various quality parameters of CPO, moisture content and Free Fatty Acid (FFA) levels are considered the most critical because they tend to fluctuate significantly during handling, processing, and storage. Consequently, continuous quality improvement efforts are required to ensure compliance with industrial standards and customer expectations. The deterioration of CPO quality is commonly associated with increasing FFA levels caused by hydrolysis and oxidation reactions occurring after the fruit is detached from the oil palm tree [6]. Excessive FFA levels may accelerate oxidative degradation, resulting in rancid odors, undesirable color changes, and reduced product quality. Several factors contribute to the increase in FFA levels, including harvesting delays, transportation conditions, equipment malfunction, processing delays, and

prolonged storage periods resulting from declining market demand. Consequently, effective quality control practices throughout all production and storage stages are essential to maintain the consistency and stability of CPO quality. Previous studies have demonstrated that improving CPO quality requires systematic control of Free Fatty Acid (FFA), moisture content, and other quality parameters through continuous improvement approaches, emphasizing the importance of timely post-harvest processing, routine quality monitoring, and structured corrective actions to minimize quality deterioration [7]. The findings of previous studies indicate that effective reduction of Free Fatty Acid (FFA) levels can be achieved through low-cost and environmentally friendly treatment methods, highlighting the importance of process optimization in maintaining CPO quality and compliance with quality standards [8]. Furthermore, quality control plays an important role not only in improving product competitiveness but also in supporting manufacturing efficiency, operational sustainability, and industrial productivity enhancement [9]. The growing focus on sustainability and industrial competitiveness highlights the importance of implementing systematic quality management and continuous improvement practices to maintain product quality and support long-term operational performance in the palm oil industry [10].

Several studies have investigated CPO quality control using statistical quality control techniques and process monitoring approaches. Previous studies have shown that quality discrepancies in CPO are often caused by worker, machinery, and method-related factors, emphasizing the need for structured improvement initiatives to effectively control Free Fatty Acid (FFA) and moisture content, thereby enhancing overall product quality and process performance [11]. Previous studies mainly focused on identifying quality deviations during production processes, while limited attention has been given to quality deterioration occurring during storage operations. In addition, studies integrating the PDCA framework with p-control charts and Fishbone Diagram analysis for quality improvement in CPO storage tanks remain relatively limited. In the investigated storage process, 54 FFA samples and 71 MC samples exceeded the established quality standards, indicating that moisture content represented the more pronounced quality deviation. The novelty of this study lies in integrating the PDCA approach with Statistical Process Control (SPC) and Fishbone Diagram analysis to systematically identify quality deviations and formulate corrective actions for reducing FFA and MC levels during CPO storage.

The proposed framework provides a practical quality improvement model that can be implemented in palm oil mills to support continuous improvement initiatives. Therefore, this study aims to evaluate the quality performance of stored CPO based on FFA and MC parameters; to identify the dominant causes of quality deterioration during storage; to formulate corrective actions using the PDCA approach to improve CPO quality performance.

2. Methods

This study was conducted at a palm oil mill located in Riau. The study utilized secondary data obtained from monthly laboratory reports generated by the quality control department. The data comprised 26 sampling periods, with samples collected from three locations within the storage tanks: the top, middle, and bottom sections. Data consisted of Free Fatty Acid (FFA) and Moisture Content (MC) measurements collected from storage tanks. Samples were taken from three different locations within the storage tanks, namely the top, middle, and bottom sections, to represent the overall quality condition of stored CPO. The analysis of Free Fatty Acid (FFA) and Moisture Content (MC) levels in Crude Palm Oil (CPO), obtained from the mill's monthly laboratory reports, indicated that the product quality had not consistently met the company's established standards and quality specifications. Consequently, improvement efforts were required to identify the root causes of quality deterioration during storage. To address this issue, the study employed the PDCA (Plan–Do–Check–Act) approach as a continuous quality improvement method aimed at enhancing storage performance, identifying the underlying causes of quality deviations, and implementing appropriate corrective actions. The research consisted of five stages: (1) data collection, (2) identification of non-conforming quality characteristics, (3) statistical analysis using p-control charts, (4) root cause analysis using a Fishbone Diagram, and (5) development of corrective actions. These stages were organized within a PDCA-based framework. The Plan stage covered problem identification and process analysis, while the Do stage focused on statistical evaluation of quality deviations. Root cause identification was conducted to support the Check stage, and corrective actions were formulated in the Act stage. Implementation and effectiveness evaluation of the corrective actions were designated for subsequent improvement cycles. Based on the company's quality specifications, samples were classified as non-conforming when FFA exceeded 3.5% and MC exceeded 0.20%. The data collected were first tabulated and grouped according to their conformity status. Subsequently,

p-control chart analysis was performed to evaluate process stability and identify the occurrence of special-cause variations during storage operations. The results of the statistical analysis were then used as input for Fishbone Diagram analysis to determine the root causes of quality deviations. Finally, corrective actions were formulated through the PDCA framework to support continuous quality improvement in CPO storage management.

The PDCA concept is widely recognized as an effective management approach for supporting continuous improvement within organizations. This method provides a systematic and structured framework for achieving sustainable quality enhancement through an ongoing improvement cycle. Previous studies have demonstrated that PDCA is effective not only for problem solving but also for identifying opportunities to improve operational processes and product quality performance in the palm oil industry [12]. The PDCA approach is applied to identify the root causes of operational issues, thereby enabling the implementation of more effective corrective measures. The PDCA cycle consists of four interconnected stages, namely Plan, Do, Check, and Act, which collectively function as a continuous improvement framework. In practice, the PDCA framework offers a comprehensive approach for evaluating process performance; however, its effectiveness largely depends on the accuracy of problem identification and the appropriateness of the corrective actions implemented [13]. Due to its systematic and flexible nature, the PDCA cycle has been widely applied across various industrial sectors as an effective tool for problem-solving and continuous quality improvement [14].

3. Result and Discussion

3.1. Plan

The initial stage of the storage tank quality control process involved collecting data on Free Fatty Acid (FFA) and Moisture Content (MC) levels that exceeded the company's established quality limits. The data were obtained from routine check sheet records maintained by the mill. Samples were collected from three sampling points representing the top, middle, and bottom sections of the storage tank. The results of the Free Fatty Acid (FFA) and Moisture Content (MC) analyses are presented below.

Table 1. Results of Free Fatty Acid (FFA) and Moisture Content (MC) Analysis

No	Sampling Point	Free Fatty Acid (%)	Moisture Content (%)
1	Top	3.64	0.19
	Middle	3.69	0.21
	Bottom	4.29	1.20
2	Top	3.76	0.17
	Middle	3.90	0.17
	Bottom	4.24	1.19
3	Top	3.92	0.22
	Middle	4.06	0.23
	Bottom	4.68	0.86
4	Top	3.97	0.21
	Middle	3.96	0.21
	Bottom	4.69	0.63
5	Top	3.87	0.22
	Middle	3.91	0.19
	Bottom	2.49	1.17
6	Top	4.18	0.28
	Middle	4.29	0.29
	Bottom	5.25	0.94
7	Top	3.00	0.76
	Middle	2.59	1.12
	Bottom	3.47	0.54
8	Top	3.56	1.08
	Middle	4.30	0.54
	Bottom	5.21	0.61
9	Top	2.71	0.91
	Middle	3.76	0.84
	Bottom	2.77	0.93
10	Top	2.53	0.78

No	Sampling Point	Free Fatty Acid (%)	Moisture Content (%)
	Middle	4.55	0.18
	Bottom	3.54	1.04
	Top	4.05	1.14
11	Middle	4.54	0.51
	Bottom	4.74	1.19
	Top	3.33	0.70
12	Middle	3.04	0.93
	Bottom	3.32	0.88
	Top	3.38	1.01
13	Middle	3.62	0.33
	Bottom	3.20	0.32
	Top	2.85	0.67
14	Middle	3.03	0.31
	Bottom	2.63	0.57
	Top	4.56	0.80
15	Middle	3.85	0.69
	Bottom	4.76	0.34
	Top	3.30	0.90
16	Middle	2.70	1.07
	Bottom	4.94	0.20
	Top	3.57	0.76
17	Middle	2.71	0.56
	Bottom	3.20	0.99
	Top	4.25	0.58
18	Middle	4.18	0.77
	Bottom	4.29	0.88
	Top	4.14	0.58
19	Middle	5.24	0.85
	Bottom	4.57	0.91
	Top	4.96	0.99
20	Middle	3.85	0.28
	Bottom	4.03	0.57
	Top	5.13	0.77
21	Middle	4.71	0.55
	Bottom	4.10	0.68
	Top	3.52	0.18
22	Middle	4.23	1.11
	Bottom	3.37	0.79
	Top	3.71	0.99
23	Middle	2.69	0.79
	Bottom	3.04	0.72
	Top	2.95	0.65
24	Middle	4.72	0.89
	Bottom	4.88	0.75
	Top	4.58	0.49
25	Middle	4.19	1.15
	Bottom	4.19	1.06
	Top	4.44	0.26
26	Middle	3.99	0.91
	Bottom	2.58	0.90

The results of the Free Fatty Acid (FFA) and Moisture Content (MC) analysis of the CPO storage samples indicated that a significant proportion of the samples exceeded the quality limits established by the company. Stored CPO is of good quality when the FFA and MC levels remain below the specified standards. Therefore,

periodic quality control measures are required to minimize elevated FFA and MC levels and to maintain consistent product quality.

3.2. Do

Non-conforming FFA and MC measurements were analyzed using p-control charts to evaluate process stability and identify special-cause variation during CPO storage. In the Do stage, the current process performance was analyzed using p-control charts to evaluate the occurrence of non-conforming FFA and MC measurements. The p-control chart was selected because the quality outcome was classified as conforming or non-conforming, making the proportion of non-conforming samples appropriate for process monitoring. Statistical Process Control (SPC) is a quality management method that focuses on monitoring and controlling processes using statistical techniques to identify process variations. This method helps reduce defects, improve productivity, and maintain product quality [15]. In addition, control charts play an important role in maintaining and improving the efficiency of manufacturing and industrial processes [16]. Performance measurement is also essential for evaluating organizational effectiveness to ensure that the company achieves its objectives and operational targets [17]. Data on FFA and MC measurements exceeding the specified quality limits are presented in Table 2.

Table 2. Data on FFA and MC Measurements Exceeding the Specified Quality Limits

Parameter	Number of Non-Conforming Samples
Free Fatty Acid (FFA)	54
Moisture Content (MC)	71

The p-control charts for FFA and MC are presented in Figures 1 and 2, respectively.

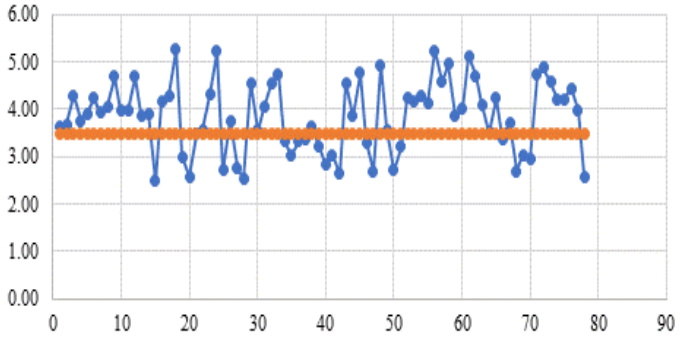


Figure 1. P-Control Chart of Free Fatty Acid (FFA) Levels

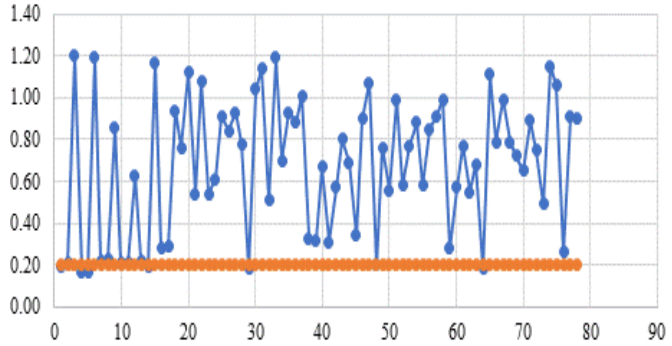


Figure 2. P-Control Chart of Moisture Content (MC) Levels

The p-control chart analysis demonstrated that several observation points exceeded the upper control limit, indicating that the storage process was statistically out of control. This indicates that the observed non-conformities were influenced by special-cause variation rather than random process variation alone, highlighting the need for targeted corrective actions. This condition reflects the presence of special-cause variations affecting the stability of CPO quality during storage. Moisture Content (MC) exhibited a higher number of non-conforming samples compared to Free Fatty Acid (FFA), suggesting that moisture-related issues represented the dominant source of quality deterioration. The instability observed in the control charts may be associated with inconsistent storage conditions, inadequate process control, delayed handling of Fresh

Fruit Bunches (FFB), and suboptimal operational practices. These findings indicate that corrective actions and continuous monitoring are necessary to improve process stability and maintain CPO quality within the established standards. The findings suggest that process instability can significantly contribute to the deterioration of CPO quality during storage. Therefore, continuous quality monitoring and systematic corrective actions are required to minimize process variation and maintain product quality within established standards. In this context, the PDCA framework provides a structured approach for improving process stability and supporting continuous quality improvement in CPO storage management.

3.3. Check

Based on the p-control chart results, a Fishbone Diagram was used to identify the potential root causes of quality deviations in stored CPO. The analysis focused on identifying factors related to human, material, machine, and method aspects that contributed to the observed quality deviations. At this stage, the evaluation was conducted using a Fishbone Diagram. The Fishbone Diagram is an analytical tool used to systematically identify the potential causes of a specific problem or effect. This diagram consists of a main horizontal line connected to several diagonal branches representing the possible root causes of the identified problem [18]. The Fishbone Diagram illustrating the quality issues associated with stored CPO is presented in Figure 3.

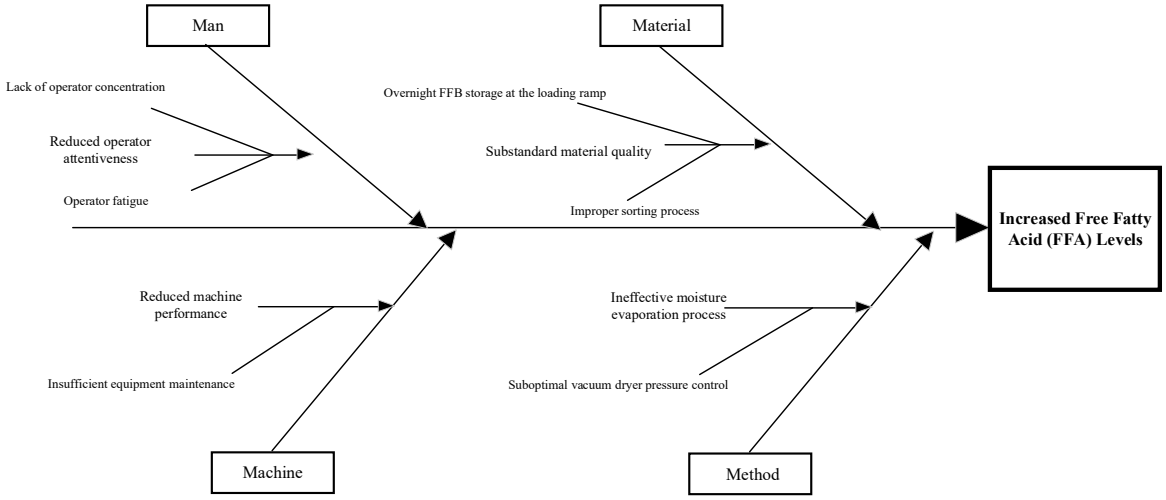


Figure 3. Fishbone Diagram of Stored CPO Quality Problems

The Fishbone Diagram analysis revealed that the quality deterioration of stored CPO was influenced by multiple interconnected factors involving human, material, machine, and method aspects. Human-related factors were primarily associated with reduced operator attentiveness and fatigue, which may affect operational accuracy and process consistency. Material-related issues were linked to prolonged storage of Fresh Fruit Bunches (FFB) at the loading ramp and ineffective sorting processes, both of which may accelerate hydrolysis reactions and increase FFA levels. This finding is consistent with previous research, which highlights the importance of controlling factors affecting FFA quality. In the present study, these factors were further linked to storage-related practices and used as the basis for developing targeted corrective actions [19]. The effectiveness of reducing Free Fatty Acid (FFA) levels has been widely recognized as a key strategy for improving CPO quality, with previous studies demonstrating that enhanced separation techniques can significantly increase FFA removal efficiency and overall product quality [20]. In terms of machine factors, insufficient equipment maintenance contributed to reduced machine performance and unstable processing conditions. Furthermore, method-related factors, particularly ineffective moisture evaporation and suboptimal vacuum dryer pressure control, were identified as major contributors to elevated Moisture Content (MC) levels. The reduction of moisture content and Free Fatty Acid (FFA) levels achieved through effective vacuum dryer operation demonstrates its important role in improving CPO quality, supporting process stability, and ensuring compliance with established quality standards [21]. These findings indicate that CPO quality deterioration is influenced not only by technical factors but also by operational and managerial practices throughout the storage and processing stages. The quality of CPO, particularly in terms of Free Fatty Acid (FFA) and moisture content, was not statistically controlled, with the observed variability primarily attributed to the processing of restan Fresh Fruit Bunches (FFB). Therefore, the implementation of a First-In-First-Out (FIFO) system is recommended to improve quality consistency and reduce quality deterioration [22].

3.4. Act

During the Action stage, corrective actions were formulated based on the findings from the previous stages to prevent the recurrence of similar problems and establish targets for future improvement initiatives. The proposed corrective actions were developed based on the root causes identified through Fishbone Diagram analysis and aligned with the continuous improvement principles of the PDCA framework. The proposed corrective actions are expected to minimize process variability, improve storage stability, enhance product quality consistency, and ensure compliance with established quality standards. The implementation of process standardization, preventive maintenance, and improved material handling practices is expected to minimize process variability and support quality improvement initiatives. Consequently, these corrective actions are anticipated to improve storage stability, enhance product quality consistency, and ensure compliance with established quality standards. The proposed corrective actions are presented in Table 3.

Table 3. Proposed Corrective Actions for CPO Storage Tank Quality Improvement

Factor	Problem Identified	Root Cause	Proposed Corrective Action	Location
Man	Reduced operator attentiveness	Lack of operator concentration	Supervisors ensure that operators are physically and mentally fit for work	Fruit Reception Station and Sterilization Station
		Operator fatigue	Provide additional rest periods to help operators regain focus	
Material	Substandard material quality	Overnight FFB storage at the loading ramp	Implement a First In First Out (FIFO) system to ensure timely processing of incoming FFB	Fruit Reception Station
		Improper sorting process	Establish clear quality standards	
Machine	Reduced machine performance	Insufficient equipment maintenance	Replace or repair damaged equipment components	Oil Clarification Station
Method	Ineffective moisture evaporation process	Suboptimal vacuum dryer pressure control	Standardization and optimize vacuum dryer pressure control procedures	Oil Clarification Station

4. Conclusion

Based on the analysis conducted using the Plan–Do–Check–Act (PDCA) approach at the palm oil mill, several quality-related issues associated with Crude Palm Oil (CPO) during storage were identified, particularly elevated levels of Free Fatty Acids (FFA) and Moisture Content (MC), which frequently exceeded the company's established quality limits. The p-control chart analysis indicated that the quality of stored CPO was statistically out of control. Furthermore, the Fishbone Diagram analysis identified several contributing factors involving human, material, machine, and method aspects. The main causes included lack of operator concentration, inadequate handling of Fresh Fruit Bunches (FFB), improper sorting processes, insufficient equipment maintenance, and suboptimal vacuum dryer pressure control procedures.

To address these issues, several corrective actions were proposed, including strengthening operator supervision, implementing a First In First Out (FIFO) system for FFB handling, establishing clear quality standards, enhancing equipment maintenance practices, and optimizing vacuum dryer pressure control procedures. The proposed corrective actions are expected to reduce the proportion of non-conforming FFA and MC samples, improve process stability, and strengthen compliance with the established quality standards. The findings of this study may serve as a reference for palm oil mills in implementing continuous quality

improvement strategies to enhance storage performance and maintain consistent CPO quality. Therefore, the research objectives of evaluating quality performance, identifying root causes, and developing improvement strategies were addressed through the PDCA-based framework. The findings of this study provide a practical basis for continuous quality improvement in CPO storage management. The use of secondary data from one palm oil mill and the available observation period provided a focused assessment of the quality conditions and contributing factors identified in the study. The proposed corrective actions offer opportunities for further implementation and evaluation in subsequent improvement cycles. Future research may extend the observation period, evaluate the effectiveness of the proposed actions after implementation, and involve multiple palm oil mills to further strengthen the applicability and generalizability of the findings.

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