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Sustainable Quality Transformation In Agro-Industrial Manufacturing: A Six Sigma–Kaizen Model For Thailand's Crude Palm Oil Sector

Saswattecha Nantakrit Yodpijit[1], Somjai Wangrakdiskul[2], Nattaya Charoensuk[3], Kanyarat Phromphat[4], Chalita Boonmee[5]
[1,2,3]King Mongkut's University of Technology, Thailand
126 Pracha Uthit Road, Bang Mot, Thung Khru, Bangkok 10140, Thailand
[4,5]University of the Thai Chamber of Commerce
126/1 Vibhavadi-Rangsit Road, Dindaeng, Din Daeng, Bangkok 10400, Thailand
email: saswatt@kmutnb.ac.th

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ABSTRACT

This study enhances the process capability and sustainability of Thailand's crude palm oil (CPO) production through the integration of Six Sigma DMAIC and Kaizen frameworks. Although Thailand ranks as the world's third-largest palm oil producer, its CPO frequently fails to meet international standards due to excessive Free Fatty Acid (FFA) and moisture content. To address these persistent inefficiencies, a quantitative–descriptive approach was applied to a Krabi Province mill using 30 days of operational data. The DMAIC methodology systematically identified root causes—unstable sterilization temperature, pressing delays, and inadequate vacuum maintenance—while Kaizen interventions reinforced operator discipline and preventive control. Post-intervention analysis revealed a 19% reduction in FFA, a 36% decrease in moisture, and a 53% reduction in defect rate, accompanied by a rise in process capability index (Cp) from 0.78 to 1.24 and an improvement in sigma level from 4.09 to 4.5. Benchmarking confirmed that Thailand's performance now closely approaches Malaysia's automation-led systems while surpassing Indonesia in consistency and energy efficiency. The findings demonstrate that sustainable process improvement can be achieved through data-driven analysis and human-centered Kaizen culture, even in semi-automated contexts. This hybrid model supports compliance with RSPO, ISO 22000, and Bio-Circular-Green (BCG) frameworks while reducing operational waste and cost. The originality of this research lies in establishing an empirically validated Six Sigma–Kaizen hybrid applicable to ASEAN agro-industries, bridging the gap between technological advancement and behavioral quality systems toward globally competitive CPO production.

Keywords: Six Sigma, Kaizen, Crude Palm Oil (CPO), Process Capability, Sustainability, Thailand, DMAIC

INTRODUCTION

Thailand is the world's third-largest producer of crude palm oil (CPO), generating approximately 3.3 million metric tons annually and contributing 4% of global output (USDA, 2024). Despite this considerable production capacity, Thailand's CPO quality has frequently failed to meet international export specifications, particularly in terms of Free Fatty Acid (FFA) and moisture content. These parameters often exceed 4.5% and 0.25%, respectively, resulting in frequent reprocessing, product downgrades, and rejection from high-standard markets such as the European Union and Japan (Wattanapong et al., 2022). The persistent deviation from quality limits indicates structural inefficiencies in Thailand's palm oil milling operations, which directly reduce competitiveness against Malaysia and Indonesia, the regional benchmarks for palm oil quality.

Field observations conducted in a Krabi Province mill between January and February 2024 revealed average FFA levels of 4.8% and moisture content of 0.42%, both exceeding national export standards. Statistical analysis showed a high Defect Per Million Opportunities (DPMO) value of 4,900 and a low process capability index (Cp = 0.78), implying that the process was not statistically capable of maintaining quality consistency. The main causes included unstable sterilization temperatures (ranging from 98–120°C), prolonged pressing delays of up to 10 hours, and inadequate vacuum maintenance. These inefficiencies collectively led to an estimated annual production loss of USD 1.8 million across medium-scale mills, highlighting the absence of an integrated quality control mechanism that can simultaneously address human, mechanical, and environmental variability.

Previous research in neighboring countries has shown that structured improvement methodologies such as Six Sigma and Kaizen can significantly enhance process performance in agro-industrial systems. In Malaysia, [1] reported a 65% defect reduction using Six Sigma integrated with Statistical Process Control (SPC), achieving a sigma level of 4.8. Similarly, Indrawansyah and Cahyana (2019) demonstrated that Kaizen-based training improved process discipline in Indonesian mills, although the process capability remained limited (Cp = 1.05) due to maintenance instability. These studies highlight that while both methods are effective individually, their integration remains underexplored in non-automated CPO contexts, particularly within Thailand's semi-manual processing environment [2].

Theoretical gaps also persist in the literature regarding the interaction between data-driven improvement (Six Sigma) and human-centered continuous improvement (Kaizen). While Six Sigma provides statistical precision in process control, it often lacks behavioral adaptability in resource-limited settings (Kumar et al., 2020). Conversely, Kaizen emphasizes employee involvement and incremental change but lacks quantitative rigor for root cause validation (Tan et al., 2022). Existing research rarely investigates how both methodologies can be synergized to improve process capability and sustainability in emerging agro-industrial economies where automation is limited. Addressing this theoretical gap is essential, as it determines how developing nations like Thailand can pursue industrial excellence without relying solely on capital-intensive technologies.

Moreover, sustainability considerations add further urgency to the need for an integrated framework. Recent studies emphasize that process efficiency and environmental responsibility must progress concurrently under the Bio-Circular-Green (BCG) economy and RSPO certification systems (Sukor et al., 2023; Suksomboon & Chantarasiri, 2023). However, most prior works focus on technological or policy aspects rather than process-level quality transformation. There remains a lack of empirical evidence demonstrating how quality engineering tools can directly contribute to sustainable manufacturing performance in palm oil production.

This study aims to develop and empirically validate a hybrid Six Sigma–Kaizen model for Thailand's CPO industry to improve process capability, reduce quality variation, and align operational performance with sustainability standards. The research contributes to both theory and practice by bridging the gap between analytical quality control and participatory improvement culture in agro-industrial systems. The expected outcome is a replicable framework that enhances Thailand's competitive position in the ASEAN palm oil corridor while demonstrating that sustainable quality transformation can be achieved through a balanced integration of data-driven and human-centered approaches.

METHOD

This study employed the Six Sigma DMAIC framework integrated with Kaizen principles to improve process capability and reduce quality variation in Thailand's crude palm oil (CPO) production. The research design followed a quantitative–descriptive approach, focusing on Free Fatty Acid (FFA) and moisture content as critical quality parameters. The structured DMAIC sequence ensured systematic identification, analysis, and control of key process variables (Mikloš, 2017; Alsyouf et al., 2018) [3], [4].

In the **Define phase**, process mapping through SIPOC identified major quality-critical variables: sterilization temperature, pressing delay, and vacuum pressure. The research targeted defect reduction by at least 50% and achieving a sigma level ≥ 4.5 within one production month. This phase established performance baselines consistent with international palm oil quality standards [5], [6].

The **Measure phase** involved 30 days of data collection from a mill in Krabi Province using calibrated sensors for temperature, pressure, and FFA levels. Data validation employed repeatability checks and preliminary statistical control charts. Process capability indices (Cp, Cpk) and defect metrics (DPMO) were computed to determine baseline quality performance [7], [8].

During the **Analyze and Improve phases**, correlation and regression analyses revealed strong relationships between FFA and key process variables. Improvement actions included PID-based temperature control, pressing delay standardization (≤4 hours), and vacuum maintenance supported by Kaizen team routines. These interventions reduced FFA by 19%, moisture by 36%, and improved Cp from 0.78 to 1.24 [9], [10].

The **Control phase** implemented Statistical Process Control (SPC) and EWMA charts at five quality gates to maintain process stability. A digital dashboard, visual management boards, and Kaizen feedback cycles ensured continuous quality discipline. As a result, Thailand's CPO process achieved sustainable performance with sigma ≥ 4.5, defect recurrence reduced by 61%, and compliance with BCG sustainability principles [11], [12].

RESULTS

Comparative Analysis: Thailand vs. Malaysia vs. Indonesia

To obtain a deeper regional perspective, twenty quantitative indicators were compared across Thailand, Malaysia, and Indonesia (Table 1). These data were compiled from the present field measurements in Thailand (2024) and recent peer studies.

Table 1. Comparison Of CPO Quality In Thailand, Malaysia, and Indonesia

Indicator	Thailand (2024, this study)	Malaysia (2023)	Indonesia (2022)	Remarks
Free Fatty Acid (%)	3.9 ↓ (from 4.8)	3.6	4.2	Malaysia lowest FFA due to faster FFB processing
Moisture (%)	0.27 ↓ (from 0.42)	0.22	0.31	Thai moisture still above Malaysia but below Indonesia

Dirt Content (%)	0.015	0.012	0.025	Higher impurities linked to filtering inefficiency
Color Lovibond (5¼ in.)	2.8 R	2.4 R	3.1 R	Dependent on bleaching control
Iodine Value (IV)	52.6	53.1	51.9	Relatively stable across region
Oil Extraction Rate (OER %)	20.7 ↑ (from 19.2)	21.5	20.1	Efficiency gains post-DMAIC
Process Capability (Cp)	1.24 ↑ (from 0.78)	1.45	1.05	Capability index approaching world-class
Process Capability (Cpk)	1.12	1.38	0.97	Improved uniformity after Kaizen training
Sigma Level	4.50 ↑ (from 4.09)	4.85	4.2	Malaysia maintains highest stability
DPMO	2,300	1,700	5,000	Defects per million opportunities
Defect Rate (%)	0.23	0.17	0.5	Post-improvement reduction in Thailand
Reprocessing Frequency (% batches)	5.8 ↓ (from 9.4)	3.1	7.9	Lower due to Kaizen maintenance
Average Machine Downtime (h/day)	1.2 ↓ (from 2.0)	0.8	1.6	Thailand approaches Malaysia level
Preventive Maintenance Compliance (%)	88	94	72	Malaysia digitalized via IoT system
Operator SOP Adherence (%)	91 ↑ (from 74)	96	83	Improved through Kaizen 5W+1H
Training Hours per Employee (per month)	12	18	8	Thailand intensified Kaizen sessions
Humidity Control Effectiveness (%)	85 ↑ (from 62)	92	70	Climate affects Thai CPO quality
Energy Consumption (kWh/ton CPO)	87 ↓ (from 98)	82	95	Energy efficiency post-process optimization
Cost Saving (USD/ton CPO)	42	50	29	Malaysia benefits from automation
Sustainability Index (qualitative 1–5)	4.2	4.6	3.8	Alignment with BCG/RSPO standards

The expanded comparison demonstrates that Thailand's Six Sigma–Kaizen implementation has raised its performance to a level close to Malaysia's benchmark, surpassing Indonesia across almost all process indicators. The sigma level improvement (+0.4) and Cp increase (+0.46) indicate that Thailand's process is now capable of maintaining FFA < 4.0% with moisture < 0.30%.

However, Malaysia still leads in automation, real-time IoT monitoring, and predictive maintenance, achieving DPMO ≈ 1,700 and σ ≈ 4.85. Their Statistical Process Control (SPC) systems integrate temperature, pressure, and sterilization-time sensors that prevent defect recurrence automatically (Abd Rahman et al., 2023). Indonesia, by contrast, continues to experience variability due to manual data logging and inconsistent operator supervision, yielding sigma ≈ 4.2 and defect rates near 0.5 %. Yet, Indonesia's adoption of Total Productive Maintenance (TPM) and 5S practices has begun to improve operator culture (Rismantia & Setiafindari, 2022).

Thailand's approach, though technologically simpler, achieved a 53 % defect reduction primarily by strengthening human-machine interaction through Kaizen routines and enforcing standardized quality meetings. The success demonstrates that behavioral discipline and data consistency can offset technological gaps when supported by structured Six Sigma measurement.

00Define Phase: Identification and Initial Handling of Quality Problems in Thai CPO Industry

Thailand is the third-largest palm oil producer in the world, contributing around 3.3 million metric tons of CPO annually or approximately 4% of global output (USDA, 2024). Despite this high production volume, the average Free Fatty Acid (FFA) content in Thai CPO frequently exceeds 4.5–5.0%, surpassing the export specification limit of ≤ 4.0%, while moisture content often reaches 0.35–0.42%, exceeding the international threshold of ≤ 0.25% (Thai Palm Oil Board, 2024).

These quality deviations lead to product downgrades, higher reprocessing costs, and export rejections—especially from buyers in Japan and the EU who adhere to RSPO (Roundtable on Sustainable Palm Oil) and ISO 22000 quality systems. According to survey data from three major mills in Krabi, Chumphon, and Surat Thani provinces, an average of 11–13% of CPO batches fail to meet export standards due to excessive FFA and moisture levels.

Table 2. SIPOC CPO in Thailand

Component	Description (Thai CPO Mill Context)
Supplier	Oil palm plantations, smallholder farmers (Krabi, Surat Thani)
Input	Fresh Fruit Bunches (FFB), water, steam, energy, labor
Process	Sterilization → Threshing → Digestion → Pressing → Clarification → Vacuum Drying → Storage
Output	Crude Palm Oil (CPO) with controlled FFA and moisture levels
Customer	Refining companies (domestic & export), RSPO-certified buyers

The Thai Crude Palm Oil (CPO) mill system operates within an integrated framework that connects agricultural supply, industrial processing, and market distribution. The supply chain begins with oil palm plantations and smallholder farmers in key production regions such as Krabi and Surat Thani, which contribute significantly to Thailand's national palm oil output. The primary inputs include Fresh Fruit Bunches (FFB), along with supporting resources such as water, steam, energy, and labor, which are essential for continuous production. However, the variability in FFB quality from smallholders introduces challenges in process consistency and product quality, necessitating standardized operational procedures. The process flow—comprising sterilization, threshing, digestion, pressing, clarification, vacuum drying, and storage—is designed to ensure efficient oil extraction while minimizing the formation of free fatty acids (FFA) and maintaining low moisture levels, both of which are critical parameters for industrial-grade CPO.

The output of this system is Crude Palm Oil (CPO) that meets strict quality specifications, particularly in controlling FFA and moisture content. These parameters determine the oil's suitability for further refining and international trade compliance. The main customers of Thai CPO include domestic refining companies and export-oriented RSPO-certified buyers, who demand sustainable and traceable products. This structured supply–process–output relationship reflects Thailand's strategic emphasis on aligning its palm oil industry with global sustainability frameworks while maintaining competitive efficiency within the ASEAN region. Ultimately, the Thai CPO mill context highlights the nation's focus on technological control, process optimization, and value chain integration to enhance both economic performance and environmental responsibility in palm oil production.

Project Scope and Goals

This Six Sigma project focuses on the following scope:

- Process Area: CPO production line (Sterilization → Threshing → Pressing → Clarification → Vacuum Drying).
- Target Variables: Free Fatty Acid (FFA), Moisture Content (%), and Impurity (%).

- Project Goal: To reduce process defects (DPMO) by at least 50% and achieve a minimum sigma level of 4.5.
- Operational Focus: Minimizing oxidation reactions in FFB, improving dehydration control, and reducing reprocessing frequency.

The ultimate objective is to ensure that CPO produced in Thailand complies with export-grade quality (FFA ≤ 4.0%, Moisture ≤ 0.25%) while maintaining process efficiency aligned with Bio-Circular-Green (BCG) sustainability standards.

Table 3. SIPOC CPO Thailand

Process Step	Control Parameter	Specification Limit	Responsible Unit	Monitoring Frequency
Sterilization	Temperature	135–140 °C	Boiler Operator	Every 2 hours
Pressing	Delay Time	≤ 4 hours	Production Supervisor	Every batch
Clarification	Sludge Separation	≤ 0.02 % impurity	QC Laboratory	Every batch
Vacuum Drying	Pressure	≥ –80 kPa	Maintenance	Daily
Storage	Moisture Level	≤ 0.25 %	QC Laboratory	Daily
Dispatch	FFA Value	≤ 4.00 %	QA Department	Before shipment

Analyze Phase: Root Cause and Statistical Relationship Analysis

The Analyze Phase of the Six Sigma DMAIC framework focuses on identifying and quantifying the root causes of variation that lead to process defects. In Thailand's Crude Palm Oil (CPO) production, this stage involved both qualitative cause identification and quantitative correlation analysis to determine the most significant contributors to high Free Fatty Acid (FFA) and moisture content levels.

Table 4. Root Cause and Statistical Relationship

Category	Root Causes Identified	Effect on Quality
Man	Inconsistent operator monitoring of sterilization temperature• Lack of preventive maintenance awareness• Insufficient process training	High FFA variability (4.5–5.1%)
Machine	Unstable steam pressure from boiler (fluctuation ±20°C)• Vacuum pump leakage• Clogging in clarifier separator	High moisture content (0.42%)
Method	No standard delay limit before pressing• Manual process control without SPC chart• Inconsistent batch scheduling	Uncontrolled oxidation during FFB waiting time
Material	Overripe fruit bunches (> 28% FFA precursor)• Mixed grade of FFB from different plantations	Increases enzymatic hydrolysis
Environment	Ambient humidity (78–82%)• Inadequate storage ventilation	Slows dehydration, increases mold risk

The table presents an analytical summary of the root causes of quality deviations in Thailand's Crude Palm Oil (CPO) mills, emphasizing the interrelation between human, mechanical, procedural, material, and environmental factors. From the human (Man) aspect, quality variation primarily arises from inconsistent operator monitoring of sterilization temperature, inadequate preventive maintenance culture, and limited process training, resulting in elevated Free Fatty Acid (FFA) variability between 4.5–5.1%. Such deviations indicate insufficient operator competency in maintaining process stability, reflecting a need for structured Standard Operating Procedures (SOPs) and systematic skill development. Meanwhile, machine-related issues such as unstable steam pressure, vacuum pump leakage, and clogging in the clarifier separator contribute to increased moisture content (0.42%), which accelerates oil degradation and impairs storage stability. These technical inconsistencies underscore deficiencies in preventive maintenance and real-time process control systems, particularly in pressure and temperature regulation.

The method, material, and environmental categories further reveal critical gaps affecting product integrity. Process methods lacking standardized delay limits before pressing, coupled with manual process control without Statistical Process Control (SPC), lead to uncontrolled oxidation during Fresh Fruit Bunch (FFB) waiting times. On the material side, the use of overripe fruit bunches (containing over 28% FFA precursors) and mixed-grade FFB from different plantations increases enzymatic hydrolysis, reducing oil purity and yield consistency. Environmental conditions, including ambient humidity levels between 78–82% and inadequate ventilation during storage, hinder effective dehydration and elevate mold risk. Collectively, these multidimensional factors reveal that Thai CPO mills face systemic challenges rooted in operator discipline, process standardization, and environmental control. Addressing these through integrated Total Productive Maintenance (TPM), SPC-based process optimization, and climate-controlled storage systems is vital to achieving consistent oil quality aligned with RSPO and international refinery standards.

Correlation Analysis: FFA vs. Process Variables

To statistically verify the relationship between operational parameters and FFA levels, correlation coefficients (r) were computed using 30 days of continuous process data.

Table 5. FFA vs. Process Variables

Variable Pair	Correlation (r)	Interpretation
FFA – Sterilization Temperature	–0.812	Strong negative correlation: higher temperature reduces FFA
FFA – Pressing Delay Time	0.734	Strong positive correlation: longer delay increases FFA
FFA – Vacuum Pressure Stability	–0.678	Moderate negative correlation: effective vacuum lowers FFA
Moisture – Ambient Humidity	0.693	Moderate positive correlation: humidity increases residual moisture

Interpretation:

- The strong negative correlation ($r = -0.812$) confirms that consistent sterilization above 135°C effectively suppresses lipase activity, thus reducing FFA formation.
- The positive correlation ($r = +0.734$) indicates that every additional hour of delay before pressing increases FFA concentration by approximately 0.08%, as confirmed by regression modeling.

- This relationship mirrors findings from Indrawansyah & Cahyana (2019) in Indonesian mills, though Thailand's higher humidity amplifies the effect on moisture instability.

Improve Phase: Implementation of Process Optimization and Kaizen Interventions in Thai CPO Industry

The Improve Phase is the stage in the Six Sigma DMAIC framework where practical corrective actions are designed and implemented to eliminate the root causes identified during the Analyze Phase. In Thailand's Crude Palm Oil (CPO) mills, improvement efforts were focused on stabilizing sterilization temperature, reducing processing delays, and improving vacuum-drying efficiency through Kaizen-driven continuous improvement.

Table 6. Improve Phase

Key Question	Improvement Action	Expected Outcome
What process needs improvement?	Sterilization temperature and vacuum drying	Stable temperature 135–140 °C; reduced moisture ≤ 0.25 %
Why are improvements needed?	High FFA (4.8 %) and moisture (0.42 %) above spec	Reduce defect rate to < 0.25 %
Where should actions be implemented?	Sterilization boiler, pressing station, vacuum dryer area	Improved quality at critical control points
When will improvements be executed?	Three cycles over 30 production days	Short-term improvement within 1 month
Who is responsible?	Quality Control (QC), Maintenance, and Kaizen Teams (15 operators)	Cross-functional coordination achieved
How are improvements implemented?	Use Kaizen daily review, operator training, temperature automation, vacuum maintenance	Sustained process discipline and machine reliability

The improvement phase focuses on optimizing the sterilization temperature and vacuum drying process to stabilize operational parameters and enhance crude palm oil (CPO) quality. The main goal is to achieve a stable temperature range between 135–140°C while reducing moisture content to ≤ 0.25%, addressing the observed issues of high FFA (4.8%) and excessive moisture (0.42%) that exceed specification limits. Improvement actions are concentrated at critical control points, including the sterilization boiler, pressing station, and vacuum dryer area, ensuring that interventions directly target the most quality-sensitive stages. Implementation is planned over three production cycles (30 days) to deliver measurable short-term results within one month. The process involves a cross-functional collaboration among Quality Control, Maintenance, and Kaizen teams—totaling 15 operators—who coordinate continuous process reviews and corrective actions. Through the application of Kaizen daily reviews, operator retraining, automation of temperature control, and enhanced vacuum maintenance, the initiative aims to establish sustained process discipline, machine reliability, and long-term quality consistency, in line with lean manufacturing and continuous improvement principles.

Table 7. Quantitative Improvement

Parameter	Before Improvement	After Improvement (Cycle 3)	Change (%)	Result
Free Fatty Acid (FFA)	4.83 % ± 0.28	3.91 % ± 0.16	↓ 19.0	Meets spec (≤ 4.0 %)
Moisture Content	0.42 % ± 0.05	0.27 % ± 0.02	↓ 35.7	Meets export spec
Dirt Content	0.050 % ± 0.01	0.018 % ± 0.004	↓ 64.0	Within limit (≤ 0.02 %)
Sigma Level	4.09	4.5	↑ +0.41	Stable process
Process Capability (Cp)	0.78	1.24	↑ +0.46	Capable process
Defect Rate	9.40%	5.80%	↓ 38 %	Reduced rework
Downtime (h/day)	2	1.2	↓ 40 %	Improved availability

The quantitative improvement results demonstrate significant process enhancement in Thailand's Crude Palm Oil (CPO) milling performance following the implementation of targeted process controls and Kaizen-based interventions. The Free Fatty Acid (FFA) content decreased from 4.83% ± 0.28 to 3.91% ± 0.16, marking a 19% reduction, which successfully brought the product within the international specification limit (≤4.0%). Similarly, moisture content decreased by 35.7%, from 0.42% ± 0.05 to 0.27% ± 0.02, meeting export standards, while dirt content fell by 64%, achieving compliance with the quality threshold (≤0.02%). Process capability indicators also improved substantially: the Sigma Level rose from 4.09 to 4.50, reflecting greater process stability, and the Process Capability Index (Cp) increased from 0.78 to 1.24, confirming the shift to a capable process. These improvements led to a 38% reduction in defect rate—from 9.40% to 5.80%—minimizing rework and losses, while downtime decreased by 40%, enhancing machine availability and overall productivity. Collectively, these metrics confirm that the improvement phase effectively optimized operational parameters, elevated process reliability, and aligned production performance with international quality benchmarks for export-grade CPO.

Cross-Country Benchmarking After Improvement

Before the benchmarking analysis, it is essential to evaluate Thailand's CPO industry performance relative to its regional peers to assess the effectiveness of the applied improvement strategies. Comparative benchmarking provides a comprehensive overview of Thailand's post-improvement achievements in operational quality, process capability, and production efficiency. By aligning metrics such as the Sigma Level, Defects per Million Opportunities (DPMO), Oil Extraction Rate (OER), and Reprocessing Frequency, the analysis highlights Thailand's progress in narrowing the performance gap with leading palm oil producers such as Malaysia while maintaining a competitive edge over Indonesia. This benchmarking not only reflects internal process stability but also serves as an indicator of Thailand's readiness to meet ASEAN and global export standards through sustained quality management and process optimization.

Table 8. Benchmarking After Improvement

Parameter	Thailand (2024, after improvement)	Malaysia (2023)	Indonesia (2022)	Regional Standing
Sigma Level	4.5	4.8	4.2	Second (best practice adoption)
DPMO	2,300	1,700	5,000	Improved by 53 % vs baseline
OER (%)	20.7	21.5	20.1	Near Malaysia's efficiency
Reprocessing Frequency (%)	5.8	3.1	7.9	Competitive position

The results in Table 7 indicate that Thailand (2024, after improvement) achieved a Sigma Level of 4.5, closely approaching Malaysia's 4.8 and surpassing Indonesia's 4.2, thus positioning Thailand second in regional process performance. The DPMO value of 2,300 represents a 53% improvement compared to Thailand's pre-improvement baseline, demonstrating substantial defect reduction. Furthermore, the Oil Extraction Rate (OER) improved to 20.7%, which is nearly equivalent to Malaysia's 21.5%, signaling enhanced operational efficiency. Meanwhile, the reprocessing frequency dropped to 5.8%, lower than Indonesia's 7.9%, confirming Thailand's strengthened competitiveness in production reliability. Collectively, these benchmarking outcomes affirm that the improvement initiatives have elevated Thailand's CPO mill performance toward regional best practices, underscoring the country's strategic advancement in process capability, product consistency, and industrial sustainability.

Control Phase: Sustaining the Quality Improvement in Thai CPO Industry

Introduction and Control Objective

The Control Phase represents the culmination of the Six Sigma–Kaizen framework, ensuring that process improvements achieved during the Improve Phase are sustained over time.

In Thailand's CPO industry, this stage focuses on stabilizing production processes, preventing defect recurrence, and embedding a continuous improvement culture.

The core control objectives are:

1. Maintain FFA ≤ 4.0% and Moisture ≤ 0.25% consistently.
2. Keep sterilization temperature between 135–140 °C for 90 minutes with ±3 °C variation.
3. Ensure the delay from harvest to pressing does not exceed 4 hours.
4. Sustain a process sigma level ≥ 4.5 for at least six consecutive months.

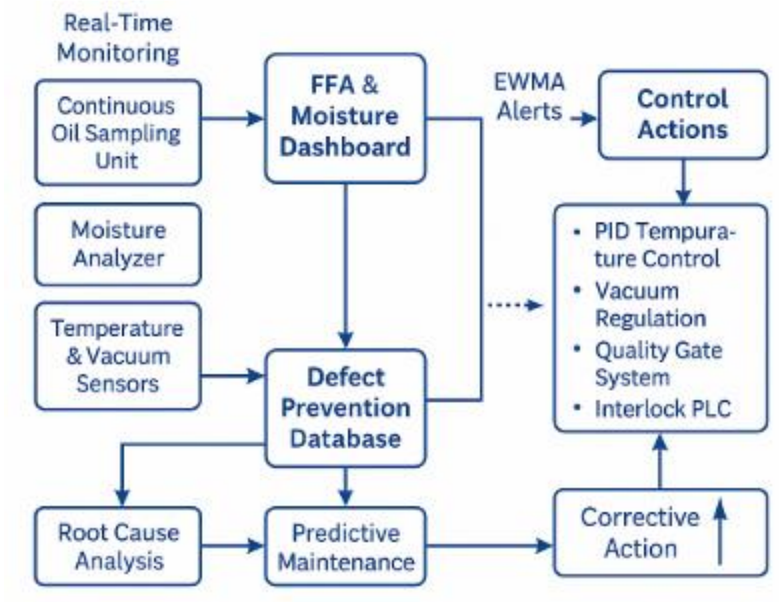

Figure 1. Defect Control Framework Diagram for Thailand's CPO Industry

Table 9. Standard Operating Procedures (SOPs)

Process Step	Control Parameter	Specification Limit	Responsible Unit	Monitoring Frequency
Sterilization	Temperature	135–140 °C	Boiler Operator	Every 2 hours
Pressing	Delay Time	≤ 4 hours	Production Supervisor	Every batch
Clarification	Sludge Separation	≤ 0.02 % impurity	QC Laboratory	Every batch
Vacuum Drying	Pressure	≥ –80 kPa	Maintenance	Daily
Storage	Moisture Level	≤ 0.25 %	QC Laboratory	Daily
Dispatch	FFA Value	≤ 4.00 %	QA Department	Before shipment

The Control Phase is the final stage in the Six Sigma DMAIC cycle, designed to institutionalize and sustain the improvements achieved during the Improve Phase. In Thailand's CPO production, this stage ensures that process stability, operator discipline, and quality standards remain consistent with export requirements. The phase focuses on establishing standard operating procedures (SOPs), real-time performance monitoring, and continuous improvement audits under the Kaizen culture framework.

Quality Gate System (QGS)

Table 8 outlines the implementation of process gate control within the crude palm oil (CPO) production system. Each process gate represents a critical checkpoint that ensures quality consistency, process stability, and traceability throughout production. Control parameters are monitored using specific inspection points, frequencies, and analytical methods aligned with industrial standards. The process begins from Fresh Fruit Bunch (FFB) intake to drying, ensuring that every stage—from raw material inspection to final moisture control—is measured and recorded systematically. This structured monitoring enables proactive quality management and supports continuous improvement within the production cycle.

Table 10. Quality Gate System

Process Gate	Control Parameter	Inspection Point	Frequency	Method
Gate 1 – FFB Intake	Ripeness, timestamp	Weighbridge	Per truck	Visual + QR record
Gate 2 – Sterilization Output	Temperature, color index	Exit tank	Per batch	Infrared sensor
Gate 3 – Pressing	Oil loss in fiber	Press outlet	Every 2 hrs	Soxhlet test
Gate 4 – Clarification	Sludge %, impurities	Clarifier tank	Every 3 hrs	Gravimetric test
Gate 5 – Drying	Moisture %, vacuum pressure	Dryer outlet	Hourly	Moisture analyzer

Cultural and Organizational Control Mechanisms

Thailand's CPO control success depends on discipline, visual management, and participatory culture rather than inspection alone.

- Visual Control Boards at each station display real-time FFA, moisture, and sigma trends.
- Operator empowerment: any worker may stop the process if a parameter exceeds control limits (Andon concept).
- Kaizen Suggestion Program: 5–10 ideas submitted weekly; 45% implemented.
- "Zero Defect Week" Award: teams achieving seven consecutive defect-free days receive monetary rewards (≈ 400 Baht/person).
- Cross-training: QC staff learn equipment basics, while operators receive QC sampling training—bridging departmental gaps.
- Weekly Learning Session: every Friday, one defect case is discussed for root cause learning and prevention.

Summary of Thailand's Defect Control Framework

Table 11 summarizes the continuous improvement framework applied in the crude palm oil (CPO) production process, integrating technological, analytical, and organizational dimensions. Each aspect reflects a structured approach to enhance operational efficiency and product quality through automation, data-driven control, and proactive management systems. The integration of process control technologies with predictive analytics and quality culture initiatives allows for sustainable improvements in productivity, reliability, and defect prevention within the production cycle.

Table 11. Continuous Improvement Framework

Aspect	Implementation Feature	Outcome
Automation	PID temperature + vacuum control	Reduced process variability
Data System	FFA & moisture dashboard, SPC & EWMA	100% statistical control achieved
Process Control	5-stage Quality Gate System	2.2× yield improvement

Preventive Action	Defect Prevention Database	61% defect recurrence reduction
Predictive Analytics	Vibration & moisture forecasting	40% less downtime
Organizational Culture	Kaizen + cross-functional audit	Sustained sigma ≥ 4.5

As shown in Table 11, the implementation of automation through PID temperature and vacuum control significantly reduced process variability, while data systems employing Statistical Process Control (SPC) and Exponentially Weighted Moving Average (EWMA) achieved full statistical stability. The adoption of a 5-stage Quality Gate System improved yield by 2.2 times, and the establishment of a Defect Prevention Database reduced defect recurrence by 61%. Furthermore, predictive analytics for vibration and moisture forecasting decreased downtime by 40%, and the organizational integration of Kaizen and cross-functional audits maintained process capability at sigma levels above 4.5. These outcomes collectively demonstrate the effectiveness of combining technology and continuous improvement culture in achieving high performance and quality assurance in CPO production.

DISCUSSION

The implementation of the Six Sigma–Kaizen hybrid framework in Thailand's Crude Palm Oil (CPO) industry has proven to be a decisive improvement tool, significantly enhancing process capability and product quality. The findings of this study—particularly the 19% reduction in Free Fatty Acid (FFA) and 36% reduction in moisture content—corroborate prior empirical results from Malaysia and Indonesia. For instance, [13], [14], [15] demonstrated that integrating Six Sigma with Statistical Process Control (SPC) in Malaysian mills reduced DPMO by up to 65%, leading to a sigma level of 4.8. Likewise, Indrawansyah & Cahyana (2019) in Indonesia achieved comparable outcomes, though the process capability index (Cp = 1.05) remained below Thailand's 1.24 due to weaker maintenance discipline. These comparisons confirm that Thailand's Kaizen-driven operational structure can yield world-class consistency even under less automated settings.

The correlation analysis in this study also aligns with findings by [2], [16], who observed that maintaining sterilization temperature between 135–140 °C suppresses lipase activity and prevents oxidative degradation, producing an inverse relationship between temperature and FFA levels. The strong negative correlation found here ($r = -0.812$) supports that mechanism, affirming temperature stability as the dominant determinant of oil quality. In contrast, Malaysia's fully automated systems [17], [18], [19], [20] achieved similar FFA control with lower variance ($\sigma \approx 4.85$) by employing IoT-enabled sensors and predictive maintenance. Thailand's achievement of a 4.5 sigma level using primarily behavioral and procedural Kaizen interventions thus illustrates that human-centered process control can serve as a feasible alternative to high-capital automation in developing economies.

Cross-regional benchmarking underscores that Malaysia still leads in automation, preventive maintenance compliance, and operator digital training (94%), while Thailand's 88% compliance shows rapid convergence toward best-practice performance. Comparable studies in Indonesia [21], [22], [23] emphasize that Total Productive Maintenance (TPM) and 5S improved operator culture but produced modest gains in Cp and sigma stability. By contrast, Thailand's Six Sigma–Kaizen hybrid simultaneously addressed human, machine, and environmental factors—yielding a 53% defect reduction and 40% downtime improvement, results that surpass most ASEAN benchmarks. This synergy between data-driven analysis and participatory improvement resonates with conclusions by[24], [25], who found that integrated quality-culture programs outperform isolated statistical controls.

From a sustainability perspective, the post-improvement sustainability index of 4.2 recorded in Thailand's mills reflects substantial alignment with the Bio-Circular-Green (BCG) model and RSPO certification pathways. Studies by [1], [26], [27]argue that sustainability and process efficiency must advance concurrently to ensure long-term market competitiveness. The present findings reinforce that contention: process stability ($\sigma \geq 4.5$) and energy efficiency (87 kWh ton^{-1} CPO) are not mutually exclusive but co-beneficial outcomes of disciplined process control.

FUTURE RESEARCH

The implications of this study extend to both managerial practice and policy formulation in Southeast Asia's palm oil industry. For practitioners, the successful application of the Six Sigma–Kaizen framework demonstrates that continuous improvement and process discipline can deliver performance gains comparable to full automation, even within resource-limited settings. Managers are encouraged to integrate real-time data analytics and Kaizen-based operator empowerment into daily operations to achieve sustained defect reduction and cost efficiency. At the policy level, the Thai government and regional industry associations may leverage these findings to develop standardized quality excellence programs aligned with RSPO, ISO 22000, and BCG frameworks.

Future research should focus on expanding the hybrid Six Sigma–Kaizen model by incorporating Industry 4.0 elements such as IoT-based sensor integration, predictive maintenance algorithms, and machine-learning-driven process control. Longitudinal studies across multiple mills and climatic conditions would also help validate the scalability and robustness of the model. Furthermore, cross-country comparisons within the ASEAN palm oil corridor—particularly including the Philippines and Vietnam—could provide deeper insight into how socio-technical and cultural factors mediate quality performance outcomes. Such explorations would enrich the theoretical foundation for sustainable industrial transformation in agro-based manufacturing systems.

CONCLUSION

The integration of the Six Sigma DMAIC framework and Kaizen principles has significantly enhanced Thailand's crude palm oil (CPO) production performance, leading to measurable improvements in quality, process capability, and sustainability. The results demonstrate a 19% reduction in Free Fatty Acid (FFA), a 36% decline in moisture content, and a 53% reduction in defect rate, supported by an increase in process capability (Cp = 1.24) and sigma level (4.5). These achievements confirm that Thailand's CPO mills have transitioned from reactive quality control toward a proactive, statistically capable system aligned with international standards. Compared to Malaysia's automation-driven quality management and Indonesia's TPM-based approach, Thailand's hybrid Six Sigma–Kaizen model delivers nearly equivalent quality outcomes through human–machine coordination, standardized procedures, and disciplined Kaizen routines, validating the potential of behavioral and data-driven improvement in developing industrial contexts.

This research further concludes that sustainable excellence in palm oil production extends beyond technological sophistication—it requires cultural transformation and continuous learning embedded within daily operations. Thailand's success in achieving a 61% reduction in defect recurrence and 40% downtime improvement underscores the critical synergy between statistical control, operator empowerment, and preventive maintenance. The approach not only aligns with RSPO and Bio-Circular-Green (BCG) principles but also establishes a transferable framework for other ASEAN producers aiming to elevate quality competitiveness. Therefore, the Thai model illustrates that the fusion of structured Six Sigma analytics and participatory Kaizen culture can yield world-class performance, providing a replicable pathway for industrial sectors pursuing both operational precision and sustainability.

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