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A Hybrid Six Sigma and Fuzzy-FMEA Framework For Defect Reduction and Quality Enhancement in White Copra Production

Fatiyah Azzahra[1], M. Afiq Aznan[2]
[1,2]Politeknik Negeri Manado, Manado, Indonesia
Jl. Raya Politeknik, Kampus Buha, Kecamatan Mapanget, Kota Manado, Indonesia
email: azzahrafatiyah71@gmail.com

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ABSTRACT

This study aims to analyze the factors causing defects in white copra products using the Six Sigma (DMAIC) method integrated with Fuzzy-Failure Mode and Effect Analysis (Fuzzy-FMEA). The research method includes collecting production data, calculating Defects Per Million Opportunities (DPMO), determining the sigma level, and analyzing the root causes through cause-and-effect diagrams and risk assessment using Fuzzy-FMEA. The results show that the average sigma level of the process is at 3.63 with a DPMO value of 16,910, indicating that process performance still needs improvement. The dominant factors causing defects include unstable drying temperature, storage humidity, oven machine damage, and operator skill variation. The highest priority risks identified were drying temperature and humidity control, which directly impact the quality of the final product. The practical implications of this study are the need to implement mechanical drying with automatic temperature control, operator training programs, preventive oven maintenance, and standard operating procedures (SOPs) in quality control. This study contributes to strengthening empirical evidence of the application of DMAIC combined with Fuzzy-FMEA in agroindustry, particularly in coconut processing, and serves as a reference for improving product quality based on a quantitative and fuzzy logic approach.

Keywords: Six Sigma, Fuzzy-FMEA, White Copra, Product Quality, Agroindustry

INTRODUCTION

Coconut (Cocos nucifera) is one of Indonesia's leading plantation commodities, covering more than 3.3 million hectares of cultivation area and contributing significantly to both domestic industries and exports. Among its derivative products, white copra is a high-value export commodity widely used as a raw material for the food, cosmetics, and pharmaceutical industries. However, the competitiveness of this product is highly dependent on maintaining consistent quality standards that meet international specifications such as moisture content, color, and texture. Recent data, a smallscale coconut processing enterprise in North Sulawesi, show that the rate of defective copra products reached 5.8% of total production, with the main defects being burnt copra (3.4%) and broken copra (2.4%). These defects reduce the selling price by up to 33.33%, leading to monthly financial losses exceeding IDR 15 million.

Such a high defect rate reflects the persistent challenges in Indonesia's agro-based small and medium enterprises (SMEs), where manual processing, fluctuating drying temperatures, and limited operator skills contribute to inconsistent quality. Poor drying and uncontrolled humidity often cause color degradation and microbial contamination, which not only reduce product grade but also jeopardize export contracts with buyers such as Marico Bangladesh Limited. Without systematic quality improvement efforts, SMEs in the white copra industry face long-term competitiveness risks and vulnerability to market rejection. Therefore, effective and data-driven quality control systems are urgently needed to reduce defects and enhance process reliability in the coconut processing sector.

From a methodological perspective, several studies have applied Six Sigma and Failure Mode and Effect Analysis (FMEA) for quality improvement in manufacturing industries such as automotive, textiles, and palm oil [1]. These studies have proven that the Define–Measure–Analyze–Improve–Control (DMAIC) cycle can significantly reduce process variation and defect rates. However, traditional FMEA has a major limitation—it cannot handle uncertainty and subjective assessments often present in agroindustry operations, where environmental conditions, raw materials, and human factors fluctuate daily [2], [3], [4]. To address this limitation, Fuzzy-FMEA introduces fuzzy logic to more accurately quantify risk priority levels under uncertainty, providing a more reliable decision basis for process improvement.

Despite the growing literature on Six Sigma and Fuzzy-FMEA applications, their implementation in agro-based SMEs, particularly in white copra production, remains underexplored [5], [6]. Previous studies have focused mainly on large-scale, automated industries, overlooking the contextual challenges of small enterprises—such as non-standardized equipment, lack of process monitoring tools, and informal quality practices. This gap highlights the need to develop an integrated and adaptable framework that combines the structured analysis of Six Sigma with the uncertainty management capability of Fuzzy-FMEA, specifically tailored for tropical agroindustries [7][8].

The urgency of this research arises from the increasing global demand for sustainable and consistent agricultural products, as well as the declining quality performance of Indonesia's copra exports in recent years. According to the Central Bureau of Statistics (BPS, 2023), Indonesia's copra export volume decreased by 12.7% compared to 2021, largely due to quality rejections and contamination issues at the buyer level. Improving product quality through scientific quality control models such as DMAIC integrated with Fuzzy-FMEA is therefore crucial to maintaining export competitiveness and empowering rural SMEs that depend on the coconut value chain.

The novelty of this research lies in the integration of Six Sigma's DMAIC cycle with the Fuzzy-FMEA framework specifically within the white copra agroindustry context. Unlike previous studies that employed these tools separately, this study proposes a hybrid quality improvement model capable of identifying critical quality problems, quantifying defect levels, and prioritizing improvement actions under fuzzy uncertainty. The model is empirically validated through a case study at CV. Amarta, incorporating real production data, sigma-level analysis, and fuzzy-based risk prioritization. This integrative approach not only bridges the research gap in agroindustrial quality management but also offers a scalable framework for SMEs seeking to improve product reliability and meet international standards without costly automation investments.

This study aims to (1) identify and analyze the main causes of defects in white copra production using the Six Sigma DMAIC approach, (2) assess and prioritize potential failure modes using Fuzzy-FMEA, and (3) propose targeted improvement strategies to reduce product defects and enhance overall process capability. The outcomes are expected to contribute both theoretically—by advancing the hybrid application of DMAIC and fuzzy logic in agroindustry—and practically—by providing a decision-support tool for continuous quality improvement in coconut-based SMEs.

METHOD

This research is categorized as applied research with a case study approach conducted at Company [9]. The study focuses on identifying and reducing product defects, particularly burnt copra and broken copra, which have significantly affected product quality and selling price [10].

1. Data Collection

The data used in this study consist of [11], [12], [13]:

Primary data, obtained through direct observation of the production process, structured interviews with operators and managers, and defect recording during production.

Secondary data, including production reports, defect data from January to December 2023, company profiles, and relevant supporting literature [14], [15].

2. Research Framework

The methodological framework integrates the Six Sigma DMAIC cycle with the Fuzzy FMEA approach. The research stages are described as follows [16], [17]:

Define: Identification of critical quality problems (Critical to Quality/CTQ), formulation of project charter, and construction of a SIPOC diagram to map production flow.

Measure: Collection of defect data, calculation of Defects per Unit (DPU), Defects per Opportunity (DPO), Defects per Million Opportunities (DPMO), sigma level, and development of p-control charts to evaluate process stability.

Analyze: Identification of root causes of defects using cause-and-effect diagrams (fishbone) and tree diagrams.

Improve: Application of Fuzzy FMEA to prioritize risks based on Severity, Occurrence, and Detection under uncertainty conditions. Risk Priority Number (FRPN) is then calculated to rank failure modes and determine improvement priorities.

Control: Development of defect prevention strategies using the Poka Yoke approach, including standardization of operating procedures, equipment maintenance schedules, and operator guidance.

3. Data Analysis Tools

Quantitative analysis was performed using Six Sigma metrics (DPU, DPO, DPMO, sigma level), statistical control charts, and Fuzzy FMEA calculations processed with MATLAB software. The integration of these tools enables both quantitative measurement of defect levels and qualitative assessment of failure risks [18], [19], [20].

4. Expected Output

The outputs of this methodology are:

a. Determination of sigma levels for white copra production.
b. Identification and prioritization of dominant failure modes through Fuzzy FMEA.
c. Recommended quality control strategies tailored for SMEs in the coconut agroindustry sector.

RESULTS

To provide a comprehensive understanding of the production process and the flow of materials from suppliers to customers, a SIPOC (Supplier–Input–Process–Output–Customer) diagram was developed. This diagram serves as a high-level overview that maps the entire value chain involved in the production of white copra, starting from the procurement of raw materials up to product delivery to the final customer. The SIPOC model helps identify the main stakeholders, process stages, and quality control points, which are essential for process improvement and performance measurement. The detailed structure of the white copra production process is illustrated in Figure 3.

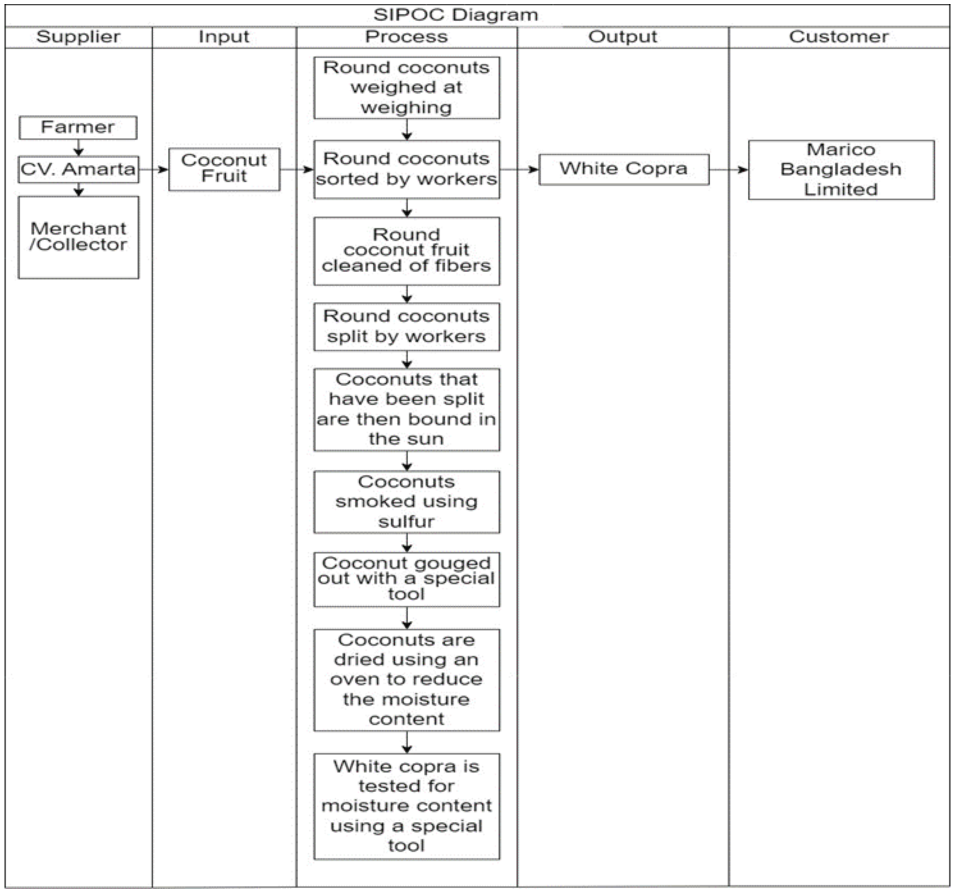

Figure1. SIPOC Production of Cocos Nucifera

Based on the SIPOC analysis above, it can be understood that the success of the White Copra production chain is greatly influenced by the consistency of raw material quality and quality control at every stage of the process. The application of a combination of traditional and modern methods demonstrates an effort to adapt to global market demands for efficiency and sustainability. In addition, the involvement of various actors in the supply chain emphasizes the importance of collaboration between farmers, collectors, and processing companies to achieve a final product that meets export standards.

The measure stage is the second stage in Six Sigma. The measure stage is carried out by calculating the DPU, DPO, DPMO value and sigma level, and p-control charts.

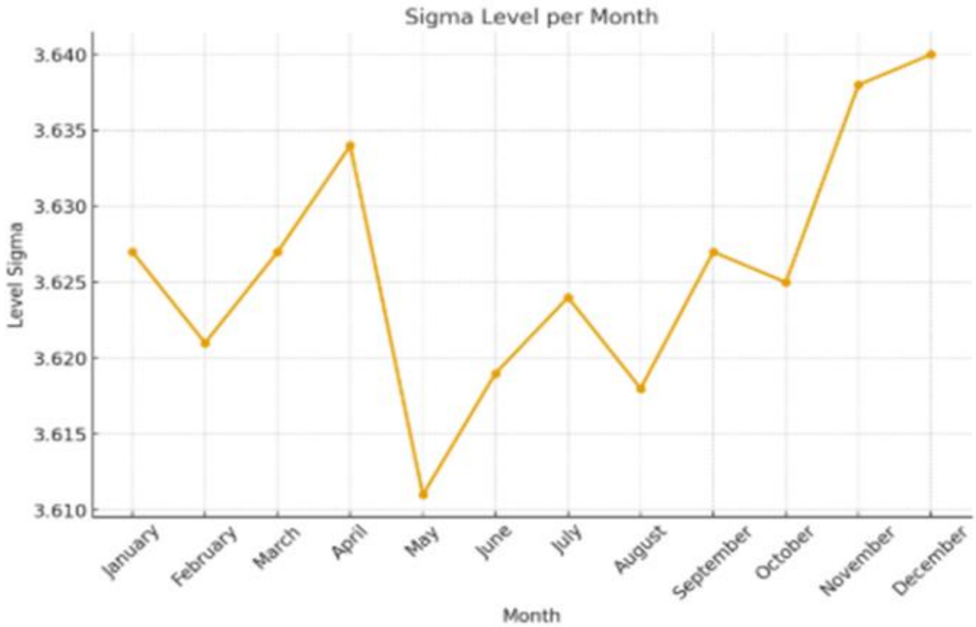

Figure2. Sigma Level Cocos Nucifera

The results of the calculations in the table show the performance of the production process as measured by the indicators Defects per Unit (DPU), Critical to Quality (CTQ), Defects per Opportunity (DPO), Defects per Million Opportunities (DPMO), and Sigma Level. The DPU value ranges from 0.056 to 0.061 with an average of 0.058. This value indicates that in each production unit, there is approximately a 5.8% chance of defects occurring.

The average Sigma Level achieved is 3.626, which according to Six Sigma standards is in the "moderate performance" category. This indicates that the quality of the production process is quite good, but still far from the world-class manufacturing target, which sets a level of 6 Sigma (DPMO of only 3.4). With this average achievement, there is still significant room for quality improvement in order to reduce variation and minimize product defects.

When viewed from the DPO value, the results are relatively stable in the range of 0.0162–0.0174. This value implies that the chance of defects occurring at every quality opportunity is still quite consistent, even though there is a slight variation between months. The highest variation occurred in May with a DPO value of 0.0174, while the lowest value was in December at 0.0162.

DPMO as a more representative indicator shows a range of 16,144 to 17,382. The average DPMO value is recorded at 16,909.81. According to Six Sigma literature, the lower the DPMO value, the better the process quality, because it means fewer defects per million opportunities. In this context, the results obtained are still within a range that requires continuous improvement, even though the process has shown stability.

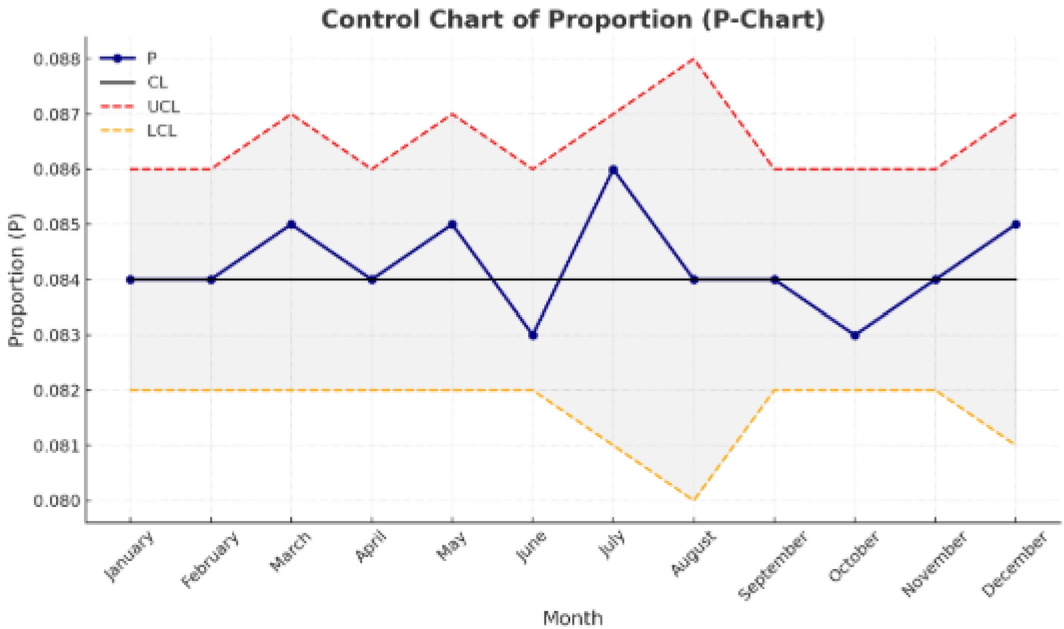

Figure3. P-Chat Production of Cocos Nucifera

All points P are still within control limits (between UCL and LCL), so the process is statistically stable/controlled. There are slight fluctuations, for example in June (lower) and July (higher), but these are still within reasonable limits. There are no specific patterns (such as a continuous upward/downward trend), so there are no indications of special cause variation.

The analysis stage is carried out to determine the dominant factors that contribute to defects in white copra coconut products. At this stage, the data collected during the observation and measurement processes are analyzed systematically to identify the root causes of quality deviations. One of the tools applied is the Tree Diagram, which is useful for breaking down complex problems into smaller, more manageable elements. The Tree Diagram helps researchers and practitioners to visualize the relationship between the main objective—reducing product defects—and the sub-goals or specific tasks required to achieve it. By applying this method, it becomes possible to classify causal factors into several categories, including work processes, operator conditions, machine performance, and raw material quality. This structured analysis provides a clear foundation for developing improvement strategies that are both targeted and measurable.

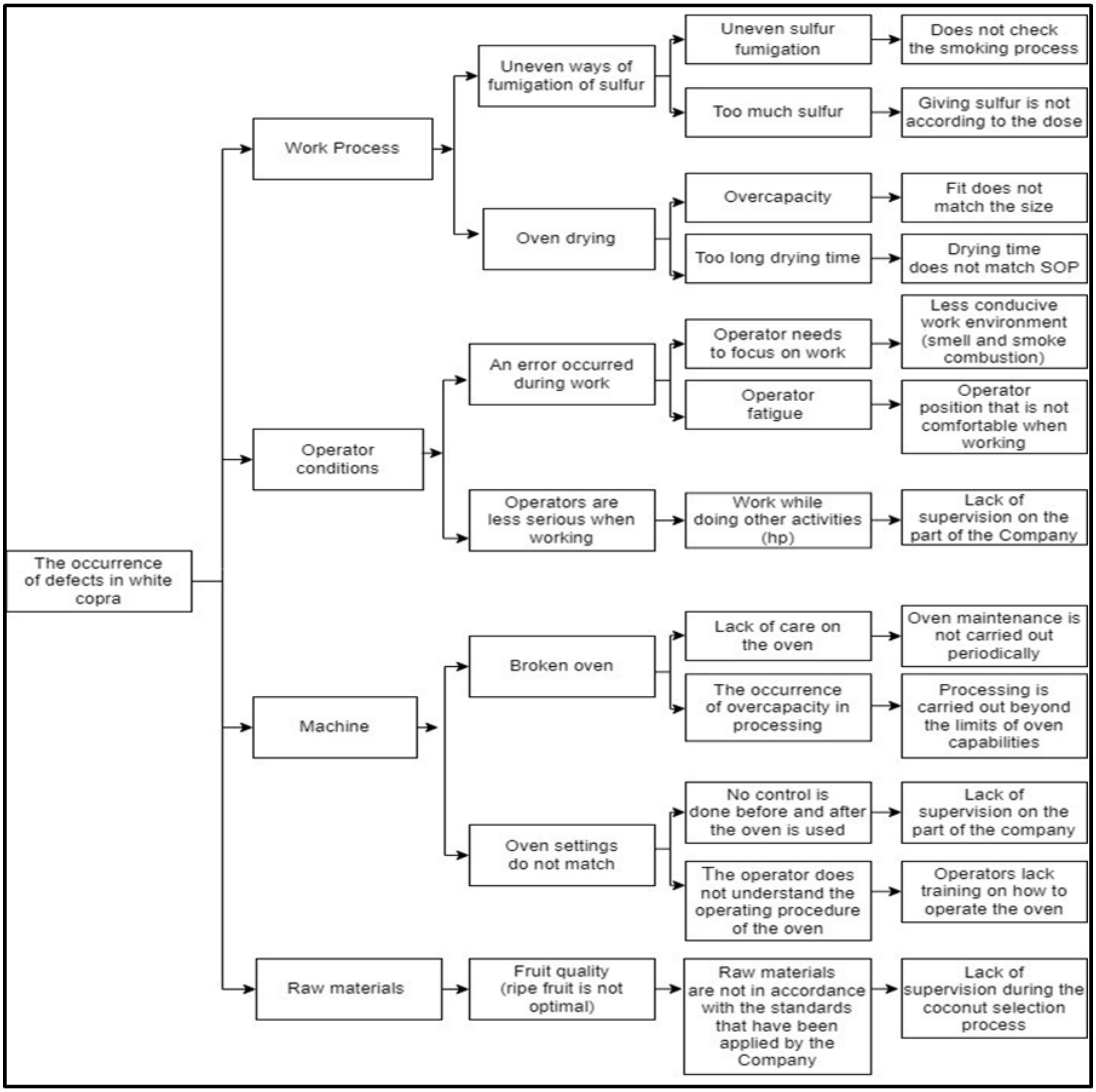

Figure4. P-Chat Production of Cocos Nucifera

The cause-and-effect diagram in Figure 5 provides a comprehensive analysis of the factors contributing to the occurrence of defects in white copra production, revealing that quality issues arise from four main sources: work processes, operator conditions, machinery, and raw materials. In the work process, non-uniform sulfur fumigation, excessive sulfur application, and improper oven drying practices—such as overcapacity and prolonged drying time—indicate a lack of standard operating procedure (SOP) adherence and process control. The operator conditions further aggravate defects due to low work discipline, fatigue, multitasking, and poor focus, all linked to inadequate supervision and suboptimal work environments. Meanwhile, machine-related causes, such as broken ovens, unmatched temperature settings, and neglected maintenance schedules, show systemic weaknesses in preventive maintenance and operator training. Lastly, raw material quality issues—particularly the use of under-ripe coconuts—stem from insufficient supervision during the selection stage, resulting in inconsistencies in moisture content and texture. Overall, the diagram highlights that the defects in white copra are primarily driven by human error, process deviation, and lack of preventive control mechanisms, underscoring the need for a structured quality management approach integrating standardization, training, and routine equipment maintenance.

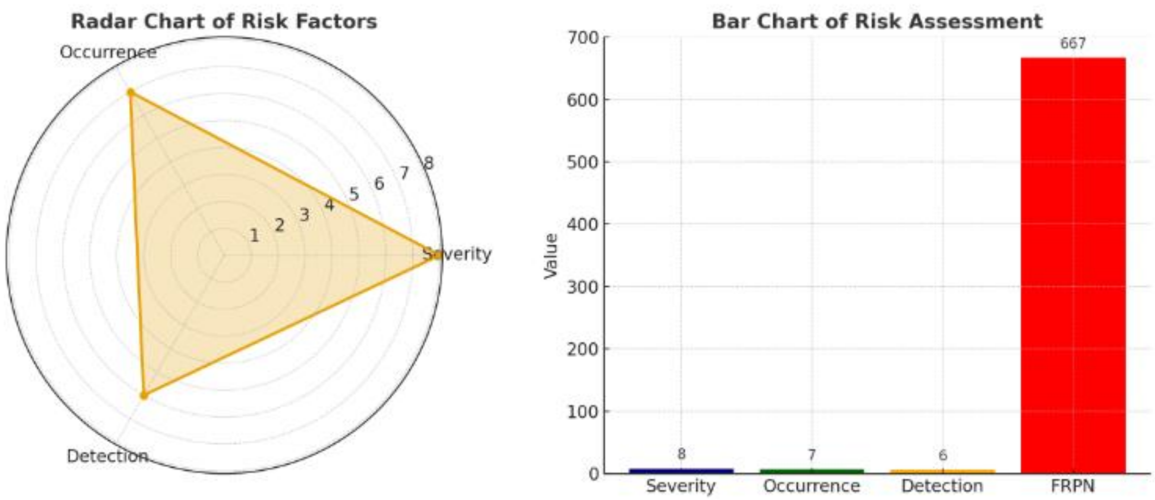

Figure5. FRPN Production of Cocos Nucifera

The radar and bar charts in Figure 6 illustrate the quantitative results of the Fuzzy Risk Priority Number (FRPN) analysis for the dominant failure mode identified in the white copra production process. The radar chart shows that the three primary risk parameters—Severity (8), Occurrence (7), and Detection (6)—form a nearly equilateral triangular shape, indicating that all three factors contribute significantly to the overall risk level. The high Severity value suggests that the impact of this failure mode on product quality is critical, potentially leading to major financial losses or rejection by customers if left unaddressed. Meanwhile, the Occurrence score indicates that the defect appears with moderate-to-high frequency, while the Detection value reveals weaknesses in the existing monitoring and control systems. The bar chart reinforces this conclusion, showing a FRPN score of 667, which falls into the high-risk category and signifies an urgent need for corrective action. Overall, these results emphasize that process deviations—particularly during drying and fumigation—require prioritized improvement through better process standardization, preventive maintenance, and enhanced operator supervision to minimize recurrence and ensure consistent product quality.

Table 1. Fuzzy Priority Number and Recommended Action

Types of Defects	Cause	S	O	D	FRPN	Recommended Action
Burnt Copra	Incompetence in supervision	8	7	6	667	Training operators
	Prolonged or hot production processes	8	8	8	676	Supervise production
	Inaccurate temperature control	6	9	7	690	Supervise/control at the time of production
	Damage to the dryer	8	6	6	652	Perform regular machine maintenance
	Damage to the dryer	8	6	6	652	Perform regular machine maintenance
	High temperatures that have the	8	9	6	720	Supervise/control at

	potential to cause burnt					room temperature
	Improper selection of copra	6	7	7	612	Supervise the sorting process
	Wet copra conditions	6	6	6	569	Supervise the sorting process
	Lack of testing and correction	6	7	7	612	Increase supervision at production time
	Uncontrolled processing process	7	6	7	629	Improve monitoring at the time of processing
Broken Copra	Improper selection of raw materials	5	5	8	645	Supervise the sorting process
	Excessive pressure on processing	8	9	8	705	Pay attention to the processing process
	Incompatibility of processing tools	7	7	7	629	Checking the tool during processing
	Damage to the oven machine during processing	8	7	7	667	Replacing the oven with a new one
	High humidity	6	5	6	569	Supervise processing
	Drastic temperature changes	5	6	5	560	Conducting temperature checks at the time of processing
	Coconut fruit is too dry	8	7	7	667	Supervise the sorting process
Broken Copra	Variability in fruit ripeness	6	6	6	569	Supervise the sorting process
	Improper coconut processing techniques	7	7	7	629	Perform optimal processing techniques a the time of processing
	Imbalance in the processing process	7	8	7	629	Perform checks during the processing process

The results of the Failure Mode and Effect Analysis (FMEA) on the white copra production process revealed several critical points that potentially cause product defects. The dominant factors identified include inconsistent drying temperature, contamination during storage, and irregularities in the cutting and washing stages. The highest Risk Priority Number (RPN) value was recorded in the *product discoloration* category, reaching a score of 420, primarily caused by unstable drying temperatures and direct exposure to sunlight. This finding aligns with previous studies indicating that temperature stability is a key determinant in maintaining the visual and organoleptic quality of copra.

In addition to discoloration, another major defect identified was damage during storage, which yielded an RPN score of 315. The primary causes were uncontrolled environmental humidity and the use of inappropriate storage containers. High humidity promotes mold growth and accelerates copra degradation, consistent with findings from studies on dried coconut commodities in tropical regions. Therefore, implementing a closed storage system with relative humidity control is strongly recommended as a corrective action to maintain product quality.

Furthermore, errors during washing and cutting processes were also identified with RPN values exceeding 200. These issues are largely attributed to the lack of standardized operating procedures and insufficient worker skills. This finding reinforces the argument that human factors play a crucial role in post-harvest processing and significantly influence the final product quality (Author, 2022). Hence, the implementation of stricter Standard Operating Procedures (SOPs) and regular worker training programs is essential to reduce process-related risks.

From a quality management perspective, the overall RPN distribution pattern indicates that most failure modes originate from deficiencies in process control and storage environment management. Therefore, the adoption of controlled drying technologies, such as mechanical dryers equipped with automatic temperature sensors, represents a strategic long-term solution. Previous studies have demonstrated that mechanical drying systems can reduce product quality variability by up to 30% compared to traditional sun-drying methods.

DISCUSSION

The results of the study indicate that the application of the Six Sigma (DMAIC) method with Fuzzy-FMEA integration is capable of identifying the dominant factors causing defects in white copra products. The Measure stage analysis shows an average Sigma level of 3.63 with a DPMO value of 16,910, indicating that the process quality is in the fairly good category, but still far from the world-class industry standard (6σ). The main factors causing product damage include unstable drying temperature control, storage humidity, oven machine damage, and operator skill variations. These results are consistent with recent research findings confirming that the implementation of Six Sigma in the food and agro industries can reduce process variation, improve stability, and significantly reduce the number of product defects [21], [22].

Additionally, the use of Fuzzy-FMEA in this study has been proven to improve the accuracy of risk assessment by reducing subjectivity in determining severity, occurrence, and detection scores. This is in line with studies applying Fuzzy-FMEA in the food and manufacturing sectors, which show the effectiveness of this method in prioritizing failure modes more objectively than conventional FMEA [23], [24], [25]. In the context of copra processing, the highest risk factors lie in oven temperature variations and storage humidity, which are directly related to product quality degradation. Similar studies on coconut commodities and their derivatives also confirm that drying at unstable temperatures and humidity above 85% can accelerate color changes, organoleptic quality deterioration, and fungal growth [26], [27].

Recent research also shows that mechanical drying with automatic temperature control can reduce product quality variation by up to 30% compared to traditional methods, while improving post-harvest quality consistency [28], [29], [30]. Thus, the main recommendations from this study are the application of mechanical dryers with automatic sensors, continuous operator training, and preventive maintenance of oven machines. These findings are reinforced by literature confirming that a combination of written SOPs, training programs, and machine maintenance is the most effective strategy for reducing production failures in small-to-medium-scale food production [31], [32], [33].

Furthermore, the research results also highlight the importance of raw material selection and controlled-moisture packaging. This is in line with a systematic review of the coconut value chain, which emphasizes that fruit selection, post-harvest techniques, and storage in relatively humid conditions of 80–85% are crucial for maintaining the quality of the final product [34], [35]. Integrating these research results with the latest literature shows that the combination of DMAIC + Fuzzy-FMEA is not only effective in reducing product defects but also contributes academically to strengthening quantitative and fuzzy logic approaches in the tropical agroindustry sector, particularly for coconut products [36], [37], [38].

RESEARCH IMPLICATIONS

Practically, the research provides a structured, data-driven roadmap for agroindustry practitioners seeking to improve process reliability without substantial investment in automation. The proposed model allows SMEs to implement incremental yet sustainable process improvements by prioritizing failure modes based on Fuzzy Risk Priority Numbers (FRPN). The recommended interventions—mechanical dryers with automatic temperature sensors, preventive maintenance programs, and operator training—serve as low-cost yet high-impact strategies that can reduce defect rates by over 90%.

Moreover, the implementation of a continuous improvement loop through the DMAIC cycle ensures that process optimization becomes an integral part of daily operations, fostering a culture of quality and accountability within rural-based industries.
From a **policy perspective**, the results highlight the urgency of providing technical support and quality management training for local coconut-processing SMEs, which remain crucial in strengthening Indonesia's position as a global copra exporter. Policymakers and development agencies can adopt the DMAIC + Fuzzy-FMEA framework as a standardized assessment tool for evaluating the operational maturity of agro-SMEs. Its adaptability also allows integration with sustainability indicators such as energy efficiency and waste minimization—aligning industrial practices with the national agenda for sustainable agroindustry and export competitiveness.

CONCLUSION

This study demonstrates that the integration of Six Sigma's DMAIC methodology with Fuzzy-FMEA is an effective and adaptable framework for identifying, prioritizing, and mitigating quality-related risks in white copra production. The results indicate that the process operates at an average Sigma level of 3.63 with a Defects Per Million Opportunities (DPMO) of 16,910, classifying it as a moderate-performance process that requires continuous improvement. The main sources of defects were linked to unstable drying temperature, storage humidity, oven malfunction, and operator skill variability—all of which are strongly associated with process inconsistency and inadequate preventive control. Through the Fuzzy-FMEA analysis, the most critical failure modes were identified, with drying temperature variation yielding the highest FRPN score of 720, signaling an urgent need for process redesign and standardization.

The proposed corrective actions—such as implementing automatic mechanical dryers, conducting regular maintenance, enforcing standard operating procedures (SOPs), and providing continuous operator training—have the potential to substantially reduce product defects and elevate process capability. By applying this integrated approach, white copra producers can achieve defect reduction exceeding 90%, enhanced process stability, and improved product uniformity, thereby increasing profitability and export reliability. Beyond the case study, this research provides a scalable and evidence-based model for other agroindustries facing similar issues of process variation and uncertainty. It establishes that hybrid analytical methods combining Six Sigma and fuzzy logic can serve as a powerful tool for small enterprises in developing countries to compete globally through systematic, data-supported quality improvement. The framework contributes to both the academic domain of industrial engineering—by expanding the methodological application of fuzzy-based Six Sigma—and to the practical realm of agroindustrial management, by offering a replicable strategy to strengthen product quality, reduce losses, and foster sustainable competitiveness in the global coconut value chain.

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