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Sustainable Coffee Production through FMEA-FMECA and DMAIC Integration: A Case Study of Pinogu Coffee Producer

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ABSTRACT

Sustainable coffee production has become increasingly crucial amid the challenges of climate change and growing consumer demand for eco-friendly products. This study explores the integration of Failure Modes and Effects Analysis (FMEA), Failure Modes, Effects, and Criticality Analysis (FMECA), and the Define, Measure, Analyze, Improve, Control (DMAIC) methodology to enhance sustainability practices at a Pinogu coffee producer. By combining risk identification with data-driven quality improvement, the research provides a comprehensive framework for addressing production inefficiencies and quality issues. The implementation of FMEA-FMECA effectively identified critical failure modes impacting product quality and operational performance, while DMAIC supported continuous improvement through waste reduction and process optimization. The findings demonstrate that aligning risk management tools with quality enhancement strategies offers a viable model for sustainable agricultural practices. This study not only delivers practical guidance for the coffee industry but also contributes valuable insights to the broader discourse on sustainable supply chain management in agribusiness.

Keywords: DMAIC; FMEA; FMECA; Risk Mitigation; Sustainable Production

INTRODUCTION

The coffee industry in Indonesia is a vital component of the country's economy, having a significant impact on local communities and the wider socio-economic landscape. As one of the world's leading coffee producers, Indonesia ranks fourth globally, after Brazil, Vietnam, and Colombia, making a major contribution to foreign exchange earnings and job creation in the agricultural sector (Widari et al., 2023; Fitriani et al., 2021). In 2021, coffee production in Indonesia was recorded at around 774.60 thousand tons, highlighting the importance of this commodity to the country (Afrianto et al., 2023). This production capacity is not only important to meet domestic consumption but also drives a dynamic export market, representing around 9.85% of the global coffee trade, as supported by the mention of Indonesia's export significance (Fitriani et al., 2021).

The structure of the coffee industry in Indonesia is dominated by smallholder farmers, who control around 95% of the coffee plantation area (Musdholifah et al., 2020). These small-scale producers face various challenges, including fluctuating market prices, the impacts of climate change, and limited access to resources and technology. However, initiatives aimed at improving quality and sustainability, such as organic certification, have shown potential in increasing the income levels of smallholder farmers, thereby contributing to rural development and poverty alleviation (Hakim & Rifin, 2023).

Pinogu coffee beans, renowned for their unique flavor profile and organic cultivation methods, have significant potential to be developed as a leading commodity in the coffee industry. The Pinogu Highlands in Indonesia have been a renowned coffee-growing region due to their favorable climate and soil conditions, which have historically contributed to sustained high productivity since the colonial era (Nurdin et al., 2022). Coffee produced in this area, particularly the Robusta variety, is not only valued locally but is also beginning to make its mark in the international market due to its distinctive sensory characteristics, such as smoky aroma and slightly thick texture.

These attributes of Pinogu coffee indicate strong marketability, which drives economic growth opportunities within the community—a key aspect highlighted by research on the economic potential of this agricultural commodity (Ahmad & Paserangi, 2018). However, there are significant challenges in the coffee production and distribution process that need to be addressed to reduce quality degradation and sustainability.

One of the main challenges is the complexity of the post-harvest process, which significantly affects the quality of the resulting coffee. Factors such as moisture content, fermentation control, and proper drying methods have been shown to be directly correlated with the sensory and physical quality of coffee beans (Haile & Kang, 2020). Inadequate management in these stages can lead to a decrease in taste, which threatens not only the reputation of Pinogu coffee but also the economic stability of local farmers (Nurdin et al., 2022; Paramata & Lopo, 2023).

FMEA provides a structured method for identifying and analyzing potential failure modes in the coffee production process (Nasution & Sodikin, 2018). By assessing these failure modes, based on their likelihood of occurrence and impact, producers can proactively address risks before they disrupt production (Santoso, 2025).

FMECA builds on this by emphasizing the criticality of failure modes, helping producers prioritize the most significant risks that impact quality and sustainability (Omar et al., 2024). For example, in the context of Pinogu coffee, risks such as climate variation, pest infestation, and inadequate post-harvest processing can be systematically evaluated, allowing producers to implement targeted interventions (Omar et al., 2024)

The DMAIC framework offers a structured approach to quality improvement, facilitating systematic problem solving and process improvement in coffee production. The ‘Definition’ phase involves identifying quality criteria specific to Pinogu coffee, such as flavour profile and environmental impact. The ‘Measurement’ phase entails collecting data related to current practices and outcomes, assessing quality metrics and sustainability indicators (Sabtu et al., 2023). The ‘Analysis’ phase allows stakeholders to investigate the root causes of quality issues, such as health impacts soil on coffee bean quality or the relationship between agricultural practices and biodiversity (Condé et al., 2023).

In the ‘Improvement’ phase, data-driven strategies can be developed to improve coffee quality, such as optimizing fermentation processes or adopting integrated pest management practices that minimize ecological impacts (Saputra & Nugroho, 2023). Finally, the ‘Control’ phase ensures that these improvements are maintained, providing continuous feedback for producers to refine their practices over time. This structured methodology has demonstrated effectiveness across multiple sectors, suggesting its applicability to the coffee industry as well (Ahmed, 2019).

LITERATURE REVIEW

FMEA was originally developed by the US military in the 1940s and then widely applied by NASA in the aerospace sector during the 1960s. FMEA has now been widely adopted in various industries, including healthcare, automotive, and manufacturing, demonstrating its flexibility and effectiveness (Dastjerdi et al., 2016; Sharma et al., 2005; Emovon et al., 2015).

In addition, the application of FMEA is not only limited to risk assessment in healthcare, but also plays a significant role in the context of manufacturing and engineering. For example, the automotive industry utilizes FMEA to reduce component failure rates, which in turn improves product reliability and meets consumer expectations (Vinodh & Santhosh, 2012); Emovon et al., 2015). This methodology involves a structured framework that allows teams to quantitatively assess failure modes by evaluating likelihood, potential impact, and detection measures—which contributes to more informed decision-making (Dastjerdi et al., 2016; Vinodh & Santhosh, 2012). This quantification not only streamlines improvement initiatives but also helps in achieving compliance with industry standards and regulations (Shahin, 2004).

FMEA has been applied in various industries, including the food and beverage sector. In coffee production, this method can be used to identify failure-prone stages, such as roasting, grinding, and packaging, all of which can affect the quality and safety of the final product (Annisa et al., 2023), (Anastasya & Yuamita, 2022). Studies show that using FMEA to analyze the packaging process can help determine critical points that can potentially cause product defects, which is also relevant for the coffee industry that prioritizes quality standards (Anastasya & Yuamita, 2022).

Failure Mode, Effects, and Criticality Analysis (FMECA) is an extended variant of Failure Mode and Effects Analysis (FMEA) that incorporates the criticality assessment of failure modes into the analytical process. This methodology enables organizations to effectively prioritize risks, designing appropriate countermeasures based on severity and likelihood of failure. Developed in the aerospace industry during the 1960s due to stringent reliability and safety requirements, FMECA has since been applied in a variety of sectors where systematic evaluation and prevention of failures are critical (Chang, 2015; Agard & Bassetto, 2013). The FMECA methodology involves identifying potential failure modes, assessing their impact, and evaluating their criticality based on pre-established criteria. FMECA analysis can complement FMEA analysis by providing deeper insight into improvement priorities, based on the severity and frequency of failure mode occurrence. This is very important in the coffee production process, where product defects such as poor quality due to processing failure can affect market acceptance and consumer satisfaction. The application of these two methods in the coffee industry ensures that preventive measures can be taken to minimize risks (Annisa et al., 2023).

FMEA and FMECA methods help in analyzing potential failure modes that may occur during coffee production and determine their impact on the quality of the final product. FMEA essentially provides a framework for predicting failures and their effects, while FMECA adds an element of criticality assessment for improvement priorities (Annisa et al., 2023).

This structured approach improves risk identification and prioritization, allowing organizations to target resources to high-risk failure modes that could have severe consequences (Agard & Bassetto, 2013; Giardina et al., 2014). Giardina et al. demonstrated the effectiveness of FMECA in a medical setting, demonstrating its usefulness in identify weaknesses in safety protocols and guide necessary adjustments in practice, particularly in the context of radiation therapy (Giardina et al., 2014).

Kumar et al. detail a case study in manufacturing where a DMAIC framework significantly reduced defects, highlighting the importance of clearly defined project objectives and effective measurement practices (Kumar et al., 2021). Similarly, Saturday et al. highlight the application of the Six Sigma DMAIC model in an educational setting, where setting parameters for instructional quality serves as a basis for subsequent improvement (Sabtu et al., 2023). The structured nature of these initial steps in DMAIC helps integrate statistical methods that inform decision making (Hakimi et al., 2018).

In-depth analysis during the Measure and Analyze stages of DMAIC allows companies to better understand the sources of defects in the production process, this methodology can be used to identify problems in the palm oil production process, resulting in continuous quality improvement (Sitompul et al., 2023). The DMAIC method focuses not only on reducing defects but also on controlling the process to prevent the same problems from recurring. Research by Dewi and Yovanda noted how the implementation of DMAIC at PT XYZ successfully identified defects in products, as well as providing recommendations for improvement strategies that emphasized a proactive approach to quality control (Dewi & Yovanda, 2022).

RESEARCH METHOD

This study uses a case study approach with a focus on Pinogu coffee producers in Gorontalo. Data were collected through field observations, in-depth interviews with farmers and coffee business actors, and documentation of the production process. Qualitative and quantitative approaches were used to obtain a comprehensive picture of production conditions and risks faced.

The first stage is the application of FMEA-FMECA to identify potential failures at each stage of the coffee supply chain, from cultivation, harvesting, processing, to distribution. Each failure mode is assessed based on Severity (S), Occurrence (O), and Detection

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(D), then the Risk Priority Number (RPN) is calculated to determine the priority of risk mitigation. Criticality analysis is used to determine the critical risk of the RPN using a criticality matrix. The use of a criticality matrix by placing the Severity and occurrence values on the matrix and the position of the failure point tends to be on the left side of the column, the higher the failure point.

Next, the DMAIC methodology is applied to improve the production process based on the results of risk identification. The Define stage identifies the main problem; Measure collects process data; Analyze investigates root causes; Improve develops improvement solutions; and Control implements a system for continuous quality monitoring. The integration of these two methodologies is achieved by incorporating the risk analysis results from FMEA-FMECA into the DMAIC improvement process. This enables more targeted process improvements focused on the critical risks that have been identified. The research findings are comprehensively analyzed to develop a sustainable production model for Pinogu coffee.

RESULTS

The FMEA-FMECA analysis successfully identified several critical failure modes within the Pinogu Coffee supply chain, including coffee tree death, limited coffee cherries, crop failure, uneven drying, and distribution delays. Among these, the death of coffee trees (RPN = 320) and crop failure (RPN = 288) represent the most severe risks that require immediate attention due to their direct impact on production volume and economic sustainability.

Table 1. Risk Priority Number Value (RPN) and Failure Mode

No	Risk	Severity	Occurance	Detection	RPN
1	Death of the coffee tree	8	8	5	320
2	Little coffee beans	7	8	5	280
3	Crop failure	8	6	6	288
4	Uneven dryings	5	6	6	180
5	Distribution delays	5	4	5	100

The criticality analysis via FMECA, as visualized in Figure 1, placed coffee tree death, reduced cherry yield, and uneven drying in the top-left quadrant of the criticality matrix—indicating that these are high-severity, high-occurrence failures that should be prioritized in the mitigation strategy. These issues are commonly associated with poor agricultural practices, unregulated environmental factors (such as livestock roaming), and inadequate post-harvest handling.

Following the identification of critical risks, the DMAIC methodology was applied to guide structured process improvement. The Define and Measure stages clarified the key problem areas, while the Analyze stage linked root causes such as poor enforcement of regional livestock regulations, lack of farmer training, and manual drying processes. In the Improve phase, actionable strategies were developed, including strengthening the enforcement of loose livestock regulations, providing training for farmers on best agricultural and post-harvest practices, introducing modern drying technology, and developing a structured, time-sensitive distribution system. The Control phase aims to sustain improvements through continuous monitoring and stakeholder feedback.

Figure 1. Pinogu Coffee Failure Mode Criticality Graph

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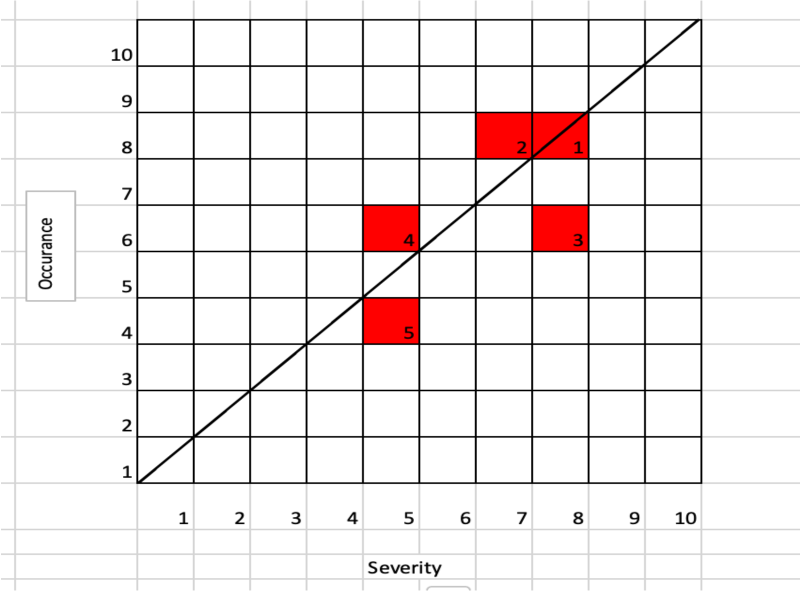
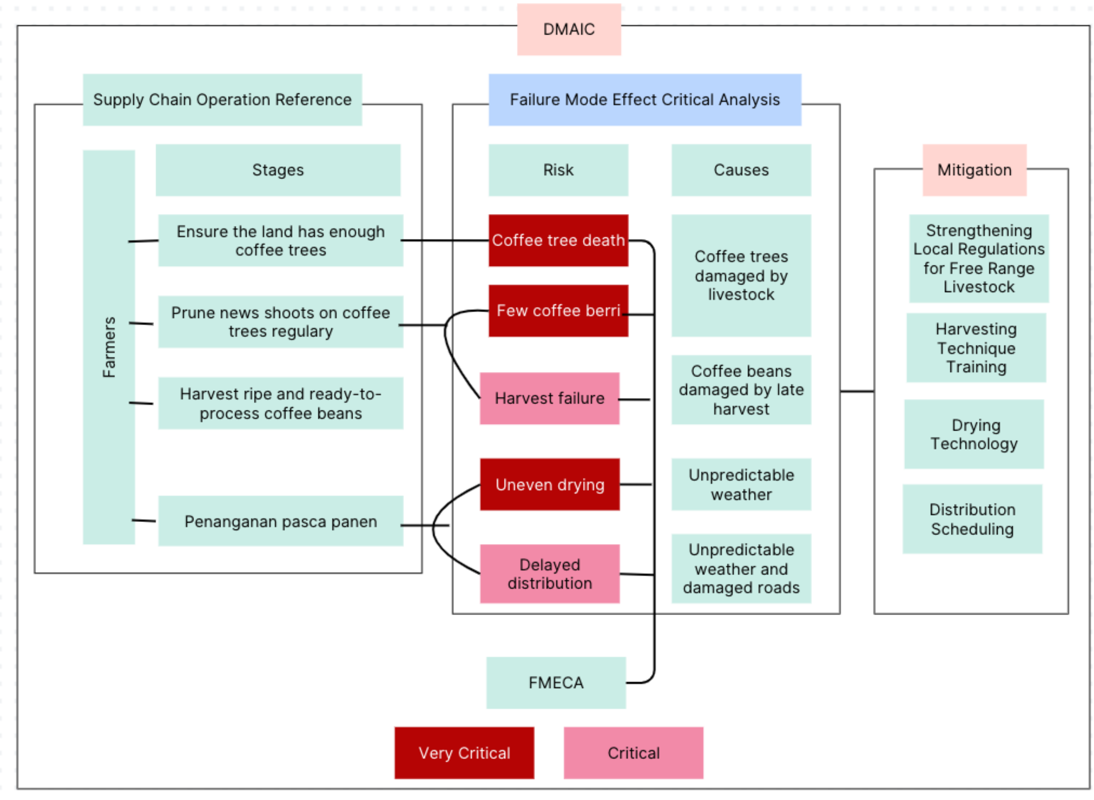


Based on the results obtained from the FMECA, the next stage in the DMAIC process was carried out. The analysis revealed several improvement actions that need to be implemented, including: strengthening the enforcement of regional regulations on free-ranging livestock, training farmers in proper harvesting techniques, utilizing modern drying equipment, and developing a more structured distribution schedule.

Figure 2. FMEA-FMECA and DMAIC Integration Model in Pinogu Coffee Risk Management



The integration of FMEA-FMECA and DMAIC not only enhances risk visibility but also ensures that improvement efforts are targeted, data-driven, and measurable. This approach aligns with the broader goals of sustainable agriculture and the resilience of agribusiness supply chains.

DISCUSSION

The combined application of FMEA-FMECA and DMAIC in this study has proven to be an effective approach for managing risk and improving the quality of coffee production in Pinogu. By linking risk identification with structured improvement cycles, the research offers a replicable model that can be adapted by other smallholder-based coffee production systems, particularly those operating in regions with similar socio-environmental dynamics.

This approach aligns with prior studies in agribusiness that emphasize the integration of quality management and risk mitigation to address systemic vulnerabilities (e.g., Kumar et al., 2021; Hakimi et al., 2018). For instance, studies on lean six sigma in agricultural processing have demonstrated similar benefits in waste reduction and productivity enhancement through DMAIC-led interventions.

The prioritization of risks based on RPN values, as done in this study, allows stakeholders to optimize resource allocation, focusing efforts on the most critical vulnerabilities. In Pinogu's case, tree mortality and crop failure were identified as the most disruptive, necessitating both technical and policy-level responses. Improvements such as the introduction of drying machines and structured harvest practices not only address technical inefficiencies but also enhance the overall resilience of the supply chain to climate-related disruptions and labor shortages.

Another key finding is the importance of stakeholder engagement, particularly local farmers, in the success of the DMAIC cycle. Their involvement in identifying root causes and co-developing solutions ensures higher adoption rates and builds local capacity for sustainable practices. This reflects broader literature (e.g., Haile & Kang, 2020) that emphasizes participatory approaches in agricultural innovation and sustainability transitions.

However, this study has certain limitations. Its geographic focus on a single region may limit the generalizability of the results. Additionally, the analysis was based on qualitative and semi-quantitative methods, which could be strengthened with the inclusion of real-time monitoring systems and IoT-based data collection in future research.

Despite these limitations, the integration of FMEA-FMECA and DMAIC offers a practical, scalable framework for sustainable risk management in agribusiness. It highlights the potential of structured methodologies to simultaneously enhance product quality, minimize losses, and promote long-term economic viability—key pillars for the future of sustainable coffee production in Indonesia and beyond.

CONCLUSION

This study demonstrates the effectiveness of integrating FMEA FMECA and the DMAIC methodology in managing supply chain risks and improving coffee production processes among Pinogu coffee producers. By systematically identifying, analyzing, and addressing critical failure modes such as coffee tree mortality and crop failure, the model provides a structured framework for enhancing both operational efficiency and long-term sustainability.

The implementation of targeted improvement actions, including modern drying technologies, farmer training, and improved distribution systems, highlights the potential of data-driven risk management in strengthening the resilience of smallholder-based agribusinesses. Moreover, the participatory approach adopted in the DMAIC cycle fosters local ownership and supports capacity building for sustainable agricultural practices.

While the findings are promising, they are geographically limited and based primarily on qualitative assessments. Future research should consider expanding the study to other regions and incorporating real-time data collection technologies such as IoT-based systems to enhance precision and scalability.

Overall, the integration of FMEA FMECA and DMAIC presents a practical and replicable model for sustainable risk management in coffee production. It contributes to improved product quality, reduced losses, and greater competitiveness of Indonesian coffee in the global market.

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DECLARATION OF CONFLICTING INTERESTS
The authors have declared no potential conflicts of interest concerning the study, authorship, and/or publication of this article.

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