Sustainable Coffee Supply Chain Risk Mitigation Analysis Using the Failure Mode and Effect Analysis

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Abstract. Coffee is one of the most important commodities and plays a crucial role in the country's economy. In East Java, Malang Regency stands out as the largest coffee plantation area, with 20,595 hectares and a production of 13,047 tons in 2021. Three key players in the coffee supply chain are: farmer groups as suppliers, Wonosantri as manufacturers, and roasters as retailers. The coffee supply chain is susceptible to risks that can hinder its sustainability. This research aims to analyze the risks in the coffee supply chain concerning sustainable coffee production. The Failure Mode and Effects Analysis (FMEA) method is employed for this purpose. FMEA identifies and assesses potential failure risks within the coffee supply chain. The results indicate seven identified risks at suppliers, seven at manufacturers, and six at roaster. The supplier's highest RPN is the risk of plant pests and diseases (A2) with an RPN of 343, the manufacturer's highest RPN is green bean defects (B4) with an RPN of 448, and the roaster's highest RPN is nondegradable packaging waste (C3) with an RPN of 392. This study concludes that FMEA is a suitable method for identifying risks and enhancing the sustainability of the coffee supply chain.

1 Introduction

Coffee is one of the plants that are a major commodity in the world of agriculture and beverage industries. The morphology of the coffee plant is very different, depending on the type of coffee. In general, coffee is a shrub or small tree that can grow to different heights depending on the type and growing conditions [1]. According to the Ministry of Industry of the Republic of Indonesia in 2019, Indonesia is the fourth largest coffee producer in the world after Brazil, Vietnam and Colombia with an average production of 700 tons annually. These results come from coffee farms spread across Indonesia, including the island of Java. Based on the Central Statistics Agency (BPS) in 2019-2021, East Java is the province with the highest coffee plantation area in Java. The plantation area has a total of 90 thousand hectares spread across all districts and cities in East Java. The process of harvesting coffee beans must be done carefully because the final quality of coffee is greatly influenced by the maturity and

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processing of the coffee beans. Once harvested, coffee beans go through a series of processing stages that include drying, shelling, and sorting [2]. Currently, Arabica and Robusta are the most commonly grown types of coffee in Indonesia.

Supply chain is a network of actors collaborating to produce and distribute a product to consumers [4]. All activities in the supply chain are controlled by the individual actors in the chain. The main actors in the supply chain are suppliers, manufacturers, retailers, and customers [3]. Presently, sustainability is an important issue and has been widely applied in the agricultural industry sector. The application of the concept of sustainability in this sector is a form of concern to maintain the survival of future generations [6]. This will have an impact on the supply chain activities and the stakeholders involved in it to also apply the concept of sustainability. Sustainability Supply Chain Management (SSCM) is a combination of conventional supply chain management concepts with sustainability concepts based on the Triple Bottom Line (TBL) concept [5]. TBL is a sustainability concept that focuses on three important aspects that are integrated with each other, namely environmental, social and economic aspects (Wan et al., 2021). The TBL concept acts as an affirmation for business people to run their businesses while paying attention to environmental safety and their contribution to society in order to achieve profitability [3].

A sustainable supply chain is a system designed to ensure the smooth, efficient, and sustainable flow of the supply chain over the long term [3]. However, various potential factors can hinder the stability and continuity of such a supply chain. Risks posed to a sustainable supply chain can have a negative impact on the continuity of activities within that supply chain [5]. Risk is an event that poses a threat, resulting in negative consequences and causing a change in objectives [7]. In the context of supply chains, risk refers to the potential for problems or disruptions that can affect the flow of goods or services from the producer to the end consumer [8]. Risks in a sustainable supply chain are like potential roadblocks that can disrupt the smooth flow of products or services from the beginning to the end of the supply chain. These risks can cause problems and negatively impact the overall goals of the business.

Wonosantri is a business unit that processes coffee, starting from seedling to green bean production. The main raw material used in green bean production is coffee beans harvested from farmer groups partnered with Wonosantri. The produced green beans are then sent to roasters for further processing until they can be consumed by consumers. This activity pattern forms a coffee supply chain consisting of three main actors: farmer groups as suppliers, Wonosantri as manufacturers, and roasters as retailers. The coffee supply chain produced by Wonosantri is also not immune to risks that can impact the sustainable supply chain. The risks occur in both the suppliers and manufacturers. Currently, Wonosantri has 6 hectares of coffee plantations managed using simple tools and faces difficulties in reaching the coffee plantations, limiting the efficiency of land management. The decline in coffee production due to poor cultivation and harvest processing has resulted in limited fulfillment of consumer demand. The abundance of defective products or defective green beans further reduces the quantity of products produced and has a significant impact on decreasing consumer fulfillment. If this condition is not addressed, it will impact Wonosantri's business processes. A sustainable supply chain risk mitigation analysis is a solution to this problem to determine the level of risk that has a significant impact on the problems that occur. Risk management has been extensively studied using various methodologies, including qualitative assessments, quantitative modeling, and hybrid approaches. While these methods have significantly contributed to identifying, assessing, and mitigating risks across different industries [25;23; 24; 22]. However, a noticeable gap remains in integrating sustainability considerations into risk management frameworks. Many studies tend to overlook long-term economic, environment, and social (Triple bottom line) risks, which are increasingly critical in today's business landscape.

This research aims to analyze the risks in the coffee supply chain concerning sustainable coffee production. Methods that can be used to analyze risks in the supply chain include Failure Mode and Effect Analysis (FMEA). FMEA is a systematic tool capable of identifying failures in a system or process and reducing or eliminating the probability of failure [9]. FMEA can used to identify potential problems or failures in a process or system. By identifying these potential problems, businesses can take steps to prevent them from happening or to minimize their impact. FMEA helps improve product quality and performance by identifying risks. This method can identify defects, optimize continuous quality control, and analyze the increase in risk priority [10]. In the context of a supply chain, FMEA can be used to pinpoint areas where things might go wrong, such as issues with suppliers, transportation, or production.

2 Research Methods

2.1 Data collection

Methods that can be used to analyze risks in the supply chain include Failure Mode and Effect Analysis (FMEA). FMEA is a systematic tool capable of identifying failures in a system or process and reducing or eliminating the probability of failure [9]. FMEA can used to identify potential problems or failures in a process or system. By identifying these potential problems, businesses can take steps to prevent them from happening or to minimize their impact. FMEA helps improve product quality and performance by identifying risks. This method can identify defects, optimize continuous quality control, and analyze the increase in risk priority (Koespratiwi et al., 2021).In the context of a supply chain, FMEA can be used to pinpoint areas where things might go wrong, such as issues with suppliers, transportation, or production.

2.2 Determine S, O, and D

Severity (S) is a value that describes the level of seriousness of the impact resulting from a failure. The higher the ranking on the scale, the higher the severity level (Rahmatin et al., 2018). The scale ranges from 1 (no effect) to 10 (catastrophic impact, such as safety hazards or regulatory non-compliance). Occurrence (O) is a value that indicates how often a failure can occur in a system or process. The higher the value of occurrence on the scale, the more frequently the failure occurs (Rahmatin et al., 2018). The scale ranges from 1 (failure is extremely unlikely) to 10 (failure occurs very frequently, almost certain to happen in normal operation). Detection (D) is a value that reflects the ability to detect a failure before it causes more serious damage. The higher the ranking on the scale, the more difficult it is to detect the failure [11]. The scale ranges from 1 (failure is easily detected and prevented) to 10 (failure is nearly impossible to detect before causing major consequences). After obtaining the values of S, O, and D, the Risk Priority Number (RPN) is calculated. The RPN value will determine the priority of risks in the coffee supply chain. The calculation of the RPN value can be seen in Equation 1.

$$S \; x \; O \; x \; D = RPN \qquad (1)$$

3 Result

3.1 Risk identification

During the risk identification stage, 21 risks were identified in the coffee supply chain. Risks with code A were identified as risks at the farmer level, risks with code B were identified as risks at the manufacturer level, and risks with code C were identified as risks at the roastery level. The identified risks considered the TBL aspects which include economic, social, and environmental factors. The identified risks can be seen in Table 1.

Table 1. Identified risk

Risk	Code	Sustainability Aspects		
		Eco	Soc	Env
Seed availability uncertain.	A1	✓		✓
The appearance of plant pests and diseases	A2			✓
Overuse of pesticides	A3			✓
Decrease in harvest yield	A4	✓		✓
Lown grade quality of coffee beans	A5	✓		
Increase in coffee bean sorting waste	A6			✓
Variations in product selling price	A7	✓		
Replacement of sales partner	A8		✓	
Reduction in coffee bean availability	B1	✓		
Warehouse capacity is limited	B2	✓		
Insufficient workforce	B3		✓	
Damaged green beans	B4	✓		
Limited waste management technology	B5			✓
Damage to machinery and equipment	B6	✓		
Green beans product damaged during shipping	B7	✓		
Decrease in order quantity	C1	✓		
Undegradable packaging waste	C2			✓
Increase in over-roasted coffee	C3	✓		✓
Employee discomfort	C4		✓	
Slow service	C5		✓	
Decrease in market share	C6	✓		

- Economic Impact (Eco)

Financial stability is threatened by risks such as decrease in harvest yield (A4) and low-grade quality of coffee beans (A5), which reduce profitability. Price fluctuations, as seen in variations in product selling price (A7), can create uncertainty for businesses. Additionally, damaged green beans (B4) and green beans damaged during shipping (B7) increase losses, while decrease in market share (C6) directly affects business competitiveness.

- Social Impact (Soc)

Risks affecting workers and society include insufficient workforce (B3) and employee discomfort (C4), which can reduce productivity and workplace well-being. Additionally, slow service (C5) and warehouse capacity limitations (B2) can disrupt supply chains, affecting customers and business partners.

- Environmental Impact (Env)

Risks such as overuse of pesticides (A3) and undergradable packaging waste (C2) contribute to environmental degradation, potentially harming ecosystems and soil quality. Similarly, increase in coffee bean sorting waste (A6) and increase in over-roasted coffee (C3) lead to excessive waste, impacting sustainability efforts.

3.2 Determine S,O, and D value

After a risk is identified, the respondent will assess it. The assessment will include the S, O, and D values for each risk. These values can be seen in Table 2.

Table 2. S,O, and D value

Code	S	O	D
A1	5	4	5
A2	7	7	7
A3	6	6	5
A4	6	7	6
A5	7	6	6
A6	6	6	6
A7	5	5	6
A8	3	3	5
B1	7	6	6
B2	7	6	5
B3	5	3	5
B4	8	8	7
B5	6	3	6
B6	7	7	5
B7	6	5	5
C1	7	7	6
C2	4	4	4
C3	7	8	7
C4	5	4	6
C5	4	3	4
C6	4	3	5

S : Severity
O : Occurance
D : Detection

3.3 Calculation of RPN value

The RPN value is calculated by multiplying the values of S, O, and D. The highest RPN value indicates that the risk is a priority risk that the company must be aware of and take action on. The calculation of the RPN value can be seen in Table 3.

Table 3. Calculation of RPN value

Code	RPN
A1	100
A2	**343**
A3	180
A4	252
A5	252
A6	216
A7	150
A8	45
B1	252
B2	210
B3	75
B4	**448**
B5	108
B6	245
B7	150
C1	294
C2	64
C3	**392**
C4	120
C5	48
C6	60

RPN : Risk Priority Number

4 Discussion

4.1 Data validation

The results of this study were validated by cross-referencing risk priority numbers (RPN) with expert evaluations and historical data within the coffee supply chain. Expert assessments from industry professionals, including farmers, manufacturers, and roasters, helped confirm the accuracy of identified risks and their impact on supply chain operations. Additionally, historical failure records and past incidents were analyzed to ensure consistency in risk identification and prioritization. This validation process strengthens the reliability of FMEA as a tool for risk assessment in the coffee supply chain.

4.2 Priority risk on farmer

The calculation of the RPN values shows that the highest risk for farmers is the appearance of plant pests and diseases (A2) with an RPN value of 343. Risk A2 is prioritized because it has a significant impact and is linked to other risks. Coffee plants infested with pests and diseases due to poor cultivation practices can lead to new risks such as decreased harvest and low coffee bean quality (Sriwana et al., 2022). The severity of borer attacks on coffee plants in Indonesia reaches 20% with a harvest loss of 50% [13]. This also occurs in coffee plants cultivated by farmer groups, posing a significant negative risk to farmers. The causes of pests and diseases in coffee plants include environmental factors and poor cultivation practices [12]. Environments with high rainfall can increase humidity, providing optimal conditions for the growth of harmful microorganisms [14]. Additionally, poor cultivation practices such as a lack of plant care also contribute to the occurrence of pests and diseases in coffee plants. The impact of this risk is a decrease in harvest due to undeveloped beans and a decrease in coffee bean quality due to holes and small bean size [15].

4.3 Priority risk on manufacture

At the manufacturing level, the highest risk is damaged green beans (B4) with an RPN value of 448. Green bean defects during production are caused by the use of poorly maintained machinery, such as dull hulling machines that cause the green beans to break[16]. Each production stage that is not carried out properly will contribute to an increase in the number of defective green bean products [17]. Green bean defects can result from hulling that causes the beans to crack, excessive fermentation that darkens the green beans, and storage in damp rooms that causes mold growth, leading to holes in the green beans [15]. Defects that occur during the production process are caused by uncontrolled processing at each stage. Additionally, poorly maintained storage warehouses can cause green bean defects due to mold, resulting in black spots and holes [18]. The increase in defective green beans during production is a significant risk that affects the quantity of green beans produced. The more defects in the beans, the lower the production of green beans [19]. This significantly affects the fulfillment of roastery needs. Moreover, this risk has a significant impact on decreased sales due to the reduced quantity of green beans.

4.4 Risk on roastery level

At the roastery level, the highest risk is an increase in over-roasted coffee (C3) with an RPN value of 392. The impact of this increase in over-roasted coffee is an increase in roasted bean waste and a decrease in the amount of roasted beans that can be sold. The waste from over-roasted coffee cannot be used and will be discarded by the roastery. In addition, roasted beans produced from over-roasting not only reduce production efficiency but also cause economic losses for the roastery because the roasted beans do not meet quality standards [20]. Over-roasted coffee beans tend to have a bitter taste and a less than optimal aroma, making them unpopular with consumers [21]. Therefore, a significant increase in over-roasted coffee can significantly reduce the amount of product, impacting the roastery's decreased revenue.

4.5 Risk mitigation

To mitigate these risks effectively, stakeholders across the coffee supply chain should implement proactive strategies. For farmers, integrated pest management (IPM) and the use of disease-resistant coffee plant varieties can help reduce the impact of plant pests and diseases. Training programs and technological interventions, such as early detection systems and precision agriculture, can further enhance resilience against agricultural risks. At the manufacturing level, improved quality control measures, enhanced sorting and storage techniques, and stricter supplier standards can minimize the occurrence of damaged green beans. Meanwhile, at the roastery stage, adopting automated roasting technology and continuous monitoring systems can help regulate temperature control, thereby reducing the risk of over-roasted coffee. Beyond risk mitigation, sustainability improvements should also be prioritized to ensure long-term viability. Implementing eco-friendly farming practices, such as organic fertilizers and agroforestry, can enhance environmental sustainability while maintaining coffee yield quality. Manufacturers and roasteries can adopt energy-efficient processing techniques, optimize resource utilization, and engage in waste reduction programs to minimize their environmental footprint. Additionally, fostering fair trade partnerships and supporting smallholder farmers through financial and technical assistance can contribute to the social sustainability of the supply chain.

5 Conclusion

Coffee is one of the primary commodities in the agricultural and beverage industries. In the industrial world, supply chain management plays a crucial role in maintaining business stability. Additionally, sustainability aspects within companies are also important to implement while considering environmental safety and contributions to society in achieving profitability. Activities in the supply chain are never free from risks. Risks arising in the sustainable supply chain can have a negative impact on the continuity of activities within that supply chain. A method that can be used to identify risks is FMEA (Failure Mode and Effects Analysis). The calculation of RPN values shows that for farmers, the highest risk is the appearance of plant pests and diseases (A2) with an RPN value of 343. At the manufacturing level, the highest risk is damaged green beans (B4) with an RPN value of 448. At the roastery, the highest risk is an increase in over-roasted coffee (C3) with an RPN value of 392. After identifying the priority risks, it is important for stakeholders to take action to minimize and prevent the negative impacts of these risks. To mitigate these risks effectively, stakeholders across the coffee supply chain should implement proactive strategies. Farmers can reduce the impact of pests and diseases by using integrated pest management (IPM) and disease-resistant coffee plant varieties, while training programs and technologies like early detection systems and precision agriculture can further enhance resilience. At the manufacturing level, improving quality control, refining sorting and storage methods, and enforcing stricter supplier standards can help minimize the occurrence of damaged green beans. Meanwhile, roasteries can prevent over-roasting by adopting automated roasting technology and continuous monitoring systems to ensure precise temperature control. Beyond risk mitigation, sustainability improvements should be prioritized for long-term viability. Farmers can adopt eco-friendly practices such as organic fertilizers and agroforestry to enhance environmental sustainability without compromising coffee yield quality. Manufacturers and roasteries can improve energy efficiency, optimize resource utilization, and reduce waste to lower their environmental footprint. Additionally, fostering fair trade partnerships and supporting smallholder farmers with financial and technical assistance can strengthen the social sustainability of the supply chain.

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