Research Article

Crafting Resilience: Innovating Risk Analysis and Mitigation Strategies in the Robusta Coffee Supply Chain Using a Fuzzy Approach

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Abstract | Focusing on resilience-building in the Robusta coffee supply chain, this study introduces an innovative risk analysis and mitigation framework utilizing fuzzy logic techniques in the context of East Java. The research addresses critical issues of uncertainty and ambiguity in risk assessment, which are often inadequately handled by traditional methods. Fuzzy Failure Mode and Effects Analysis (FMEA) and the Fuzzy Analytical Hierarchy Process (AHP) were employed to identify, evaluate, and prioritize potential risks and mitigation strategies. Data was collected from 150 respondents, including 80 farmers, 30 processors, 20 distributors, and 20 local government officials. Unlike conventional risk analysis methods that rely on precise numerical inputs, fuzzy logic incorporates subjective perceptions and imprecise data, making it particularly effective in addressing complex and uncertain conditions. This study reveals the applicability of fuzzy techniques in enhancing supply chain resilience by providing a flexible and realistic approach to decision-making. The study revealed enhanced pest management, improved irrigation systems, crop diversification, and infrastructure development as the most effective mitigation strategies against climate-related supply chain risks. Based on these findings, practical recommendations were proposed for farmers, policymakers, and supply chain managers to strengthen resilience and sustainability within the Robusta coffee supply chain. This research contributes to supply chain risk management by applying fuzzy-based FMEA and AHP techniques, offering a structured and adaptable framework for analyzing uncertainties and prioritizing risk mitigation strategies in agricultural contexts.

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Introduction

The coffee industry represents a crucial component of the global agricultural sector, contributing over USD 100 billion annually to the world economy and supporting the livelihoods of more than 125 million people across more than 70 countries, particularly in developing regions (Voora *et al*., 2019). As one of the most widely consumed beverages, coffee, particularly Robusta coffee (*Coffea canephora*), holds a strategic position in regions with favorable growing conditions, such as Indonesia (Kath *et al*., 2020). The

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Robusta coffee supply chain encompasses a series of interconnected activities, including cultivation, harvesting, processing, distribution, and consumption (Ruhyana *et al.*, 2022). However, despite its significant economic importance, the coffee supply chain faces numerous challenges, including climate variability, pest and disease outbreaks, fluctuating market prices, limited access to infrastructure, and inconsistent quality control. Among these, climate variability and pest outbreaks are considered the most critical risks, as they directly affect production yields and threaten the long-term sustainability of the supply chain.

One of the primary challenges in the Robusta coffee supply chain in East Java is its vulnerability to risks arising from climate variability, market dynamics, socio-economic factors, and infrastructural limitations. Climate variability, including extreme weather events, has significantly impacted coffee production by affecting crop yields, quality, and susceptibility to pests and diseases (Jawo *et al.*, 2023). Additionally, fluctuations in coffee prices and market demand have led to unstable income and livelihoods for coffee farmers (Campbell, 2021). Socio-economic issues, such as labor shortages, inadequate infrastructure, and socio-political instability, further exacerbate the complexities of the supply chain (Hochachka, 2023).

In response to these challenges, there is an increasing awareness of the need for innovative methodologies and strategies to enhance the resilience of the Robusta coffee supply chain. Traditional risk management approaches often fail to adequately address the uncertainties and complexities inherent in modern supply chains (Gurtu and Johny, 2021; Olufunke *et al.*, 2024). This gap underscores the importance of leveraging advanced analytical techniques and decision-making tools, such as Fuzzy Logic, to improve risk analysis and mitigation efforts.

Fuzzy logic in supply chain risk management

Fuzzy logic, first introduced by Zadeh (1965), provides a flexible framework for modeling and reasoning under uncertainty, vagueness, and imprecision (Reyes-García and Torres-García, 2022). Unlike traditional binary logic, which operates on absolute values, fuzzy logic accommodates degrees of truth, making it particularly suitable for addressing the nuanced nature of risks in complex systems like supply chains. For instance, climate variability impacts coffee yields differently across years, and fuzzy logic allows stakeholders to evaluate these impacts within a range of potential outcomes rather than fixed values.

In the context of the Robusta coffee supply chain, fuzzy logic techniques such as Fuzzy Failure Mode and Effects Analysis (FMEA) and Fuzzy Analytical Hierarchy Process (AHP) are particularly valuable. Fuzzy FMEA enables the identification, evaluation, and management of risks by integrating subjective perceptions and imprecise data, while Fuzzy AHP facilitates the prioritization of mitigation strategies based on multi-criteria decision-making (Deiva Ganesh and Kalpana, 2022; Maskrey *et al.*, 2022). These tools offer significant advantages over traditional methods by addressing the ambiguity and subjectivity often encountered in agricultural supply chains.

Diagram of existing and proposed supply chain

To illustrate the challenges and proposed solutions more effectively, Figure 1 presents the existing Robusta coffee supply chain framework in East Java, which operates under traditional risk management approaches. This framework highlights key stakeholders such as farmers, processors, distributors, and exporters, along with the associated risks, including climate variability, price volatility, and socio-economic constraints.

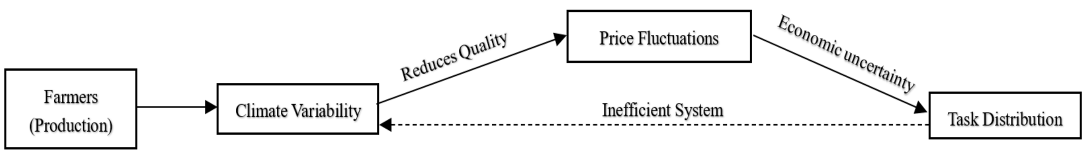

Figure 1: *Traditional robusta coffee supply chain framework in East Java.*

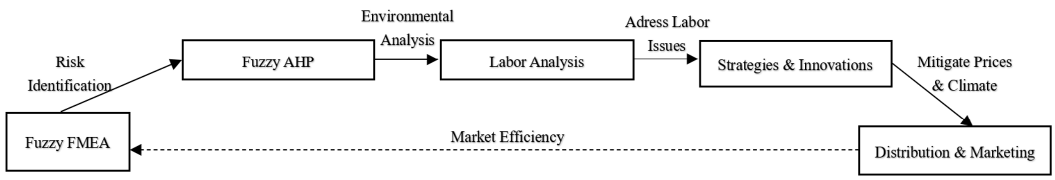

Figure 2: *Proposed fuzzy-integrated supply chain framework for risk mitigation.*

Meanwhile, Figure 2 showcases the proposed supply chain framework integrated with fuzzy-based methodologies. This framework emphasizes the role of fuzzy logic in identifying and mitigating risks at each stage of the supply chain, enabling a more resilient and adaptive system.

For instance, in the proposed model:

- Fuzzy FMEA evaluates the likelihood and severity of risks such as pest outbreaks or labor shortages, providing stakeholders with a more nuanced understanding of potential disruptions.
- Fuzzy AHP prioritizes mitigation strategies based on impact, cost, and feasibility, facilitating more informed decision-making.
- This study utilizes conceptual diagrams to map key supply chain challenges and to demonstrate the application of fuzzy-based approaches in enhancing risk analysis and mitigation.

Research objectives and contribution

This study explores the application of fuzzy logic to address the unique challenges and uncertainties faced by stakeholders in the Robusta coffee supply chain in East Java. By leveraging Fuzzy FMEA and Fuzzy AHP, this research aims to:

- Enhance the accuracy and realism of risk assessments.
- Develop tailored mitigation strategies to improve supply chain resilience.
- Contribute to the existing body of knowledge on agricultural supply chain risk management through the integration of advanced fuzzy methodologies.

This research represents a novel and interdisciplinary effort to innovate risk analysis and mitigation strategies in the coffee industry. The findings are intended to offer actionable insights and evidence-based recommendations to support stakeholders including farmers, policymakers, and supply chain actors in managing risks and enhancing the resilience of the Robusta coffee supply chain.

Materials and Methods

This study focuses on the Robusta coffee supply chain in East Java, Indonesia, particularly in Malang Regency. East Java is renowned for its favourable agro-climatic conditions, which are conducive to the cultivation of Robusta coffee. The region's climate, soil, and topography provide an ideal environment for growing high-quality Robusta coffee beans. The study area was chosen due to its significant contribution to the Indonesian coffee industry and its susceptibility to various risks that threaten the sustainability and resilience of the supply chain.

Data collection

Data for this study were collected through a combination of primary and secondary sources. Primary data collection involved conducting semi-structured interviews with key stakeholders in the Robusta coffee supply chain, including farmers, processors, distributors, and local government officials. These interviews aimed to gather detailed insights into the risks faced by the supply chain and the current risk management practices. Additionally, structured questionnaires were distributed to a larger sample of stakeholders to quantify the prevalence and impact of various risks identified during the interviews. The surveys covered climate variability, market fluctuations, socio-economic factors, and infrastructural challenges. Secondary data collection included a comprehensive literature review on supply chain risk management, fuzzy logic applications, and the coffee industry to provide a theoretical foundation for the study. Furthermore, historical data on coffee production, weather patterns, market prices, and other relevant metrics were gathered from government reports, industry publications, and academic sources.

The study involved 150 respondents, comprising key stakeholders from various sectors of the Robusta coffee supply chain in East Java. Respondents were selected using purposive sampling, based on their active roles and experience in coffee production, processing, distribution, or policymaking. This approach ensured the inclusion of individuals with relevant knowledge and decision-making capacity regarding supply chain risks and mitigation strategies. Among them were 80 farmers actively engaged in coffee cultivation, 30 processors involved in the coffee bean processing phase, 20 distributors responsible for transporting coffee products, and 20 local government officials overseeing regulatory aspects and infrastructure development within the region, was based on a detailed analysis of the supply chain structure and stakeholder roles in the region. This distribution reflects the key players involved in each stage of the supply chain, from cultivation to distribution and regulatory oversight. Data from local agricultural reports and supply chain surveys indicated that this composition mirrors the actual distribution of roles within the supply chain, making the sample representative of the sector's key stakeholders.

Risk identification and assessment
The risk identification and assessment process involved the following steps:

Risk identification: A panel of experts was consulted using the Delphi method to identify the primary risks affecting the Robusta coffee supply chain. The Delphi method is an iterative process that involves multiple rounds of surveys and feedback to achieve a consensus among experts. The Delphi method used in this study involved a structured iterative process to achieve consensus on the key risks affecting the Robusta coffee supply chain. This process consisted of three rounds of questionnaires. In the first round, experts provided initial assessments of risk factors. The second round involved feedback on the initial responses, with experts reassessing their answers based on the group's feedback. The third round focused on refining and finalizing the risk factors, ensuring a high level of agreement among experts. This iterative approach helped in achieving a well-rounded consensus on the most critical risks and their impacts, enhancing the reliability of the risk assessment (Table 1).

Fuzzy failure mode and effects analysis (FMEA): FMEA was employed to evaluate and prioritize the identified risks. Traditional FMEA was enhanced with fuzzy logic to handle the uncertainty and ambiguity in risk assessment (Table 2). The steps involved in Fuzzy FMEA are as follows:

- Risk Factors: Defining the risk factors such as severity, occurrence, and detection.
- Fuzzy Logic Application: Applying fuzzy logic to transform qualitative assessments into quantitative scores.
- Risk Priority Number (RPN): Calculate the fuzzy RPN for each risk by combining the fuzzy scores of severity, occurrence, and detection scores.

The implementation of Fuzzy Failure Mode and Effects Analysis (FMEA) in this study utilized the Fuzzy Logic Toolbox in MATLAB for computational analysis. This software allowed for precise fuzzification and defuzzification of risk factors, providing a robust framework for handling the inherent uncertainties in risk assessment. The fuzzy risk priority numbers (RPNs) were calculated using triangular fuzzy numbers (TFNs) to represent the severity, occurrence, and detection of risks. The use of MATLAB facilitated efficient processing of these fuzzy calculations and enabled detailed analysis of risk impacts on the Robusta coffee supply chain.

Table 1: *Defining risk factor.*

Risk factor	Description
Severity (S)	Impact of the risk if it occurs, categorized as Low (1-3), Medium (4-6), or High (7-9).
Occurrence (O)	Likelihood of the risk occurring, categorized as Rare (1-3), Possible (4-6), or Likely (7-9).
Detection (D)	Ability to detect the risk before it occurs, categorized as Easy (1-3), Moderate (4-6), or Difficult (7-9).

Table 2: *Fuzzification of risk factors.*

Risk factor	Linguistic terms	Triangular Fuzzy numbers (TFNs)
Severity (S)	Low, Medium, High	Low (1, 2, 3), Medium (4, 5, 6), High (7, 8, 9)
Occurrence (O)	Rare, Possible, Likely	Rare (1, 2, 3), Possible (4, 5, 6), Likely (7, 8, 9)
Detection (D)	Easy, Moderate, Difficult	Easy (1, 2, 3), Moderate (4, 5, 6), Difficult (7, 8, 9)

Prioritization of mitigation strategies
To prioritize the risk mitigation strategies, the Fuzzy Analytical Hierarchy Process (AHP) was utilized:

- Criteria Definition: Identifying the criteria for prioritizing mitigation strategies, such as potential impact, implementation cost, and resource availability.
- Pairwise Comparison: Conduct pairwise comparisons of the criteria and the mitigation strategies using fuzzy scales to account for subjective judgments.
- Fuzzy AHP Calculation: Using fuzzy AHP to derive each criterion's priority weights and rank the mitigation strategies accordingly.

Simulation and validation
Monte carlo simulation: Monte Carlo simulation was performed to test the reliability and robustness of the fuzzy FMEA and AHP models under different scenarios. This method involves running many simulations to account for variability and uncertainty in the input data. Monte Carlo simulation was employed to test the robustness of the fuzzy model by simulating various risk scenarios and their impacts

on the coffee supply chain. This simulation involved running thousands of iterations with varying risk inputs to assess the stability and reliability of the fuzzy model's predictions. By analyzing the range of potential outcomes and their probabilities, the simulation provided insights into the model's performance under different risk conditions, thus ensuring that the fuzzy analysis accurately reflects real-world uncertainties and enhances the reliability of the risk management strategies proposed.

Historical data comparison: The fuzzy models' results were compared with historical data on risk occurrences and impacts in the Robusta coffee supply chain to ensure their validity and applicability.

Implementation: The final step involved developing practical stakeholder guidelines based on the study's findings. This step included creating comprehensive risk mitigation plans tailored to the specific needs and conditions of the Robusta coffee supply chain in East Java. Additionally, conducting workshops and training sessions for stakeholders was prioritized to disseminate the research findings and enhance their capacity in risk management using fuzzy logic techniques. By employing a combination of fuzzy FMEA and AHP, this study aims to provide a robust framework for risk analysis and mitigation in the Robusta coffee supply chain, ultimately enhancing its resilience and sustainability.

Result and Discussion

This study focuses on applying fuzzy logic to risk analysis and mitigation in the Robusta coffee supply chain in East Java. The findings are based on data collected from primary and secondary sources and the application of Fuzzy Failure Mode and Effects Analysis (FMEA) and Fuzzy Analytical Hierarchy Process (AHP).

Fuzzy failure mode and effects analysis (FMEA)

Identification of risk factors: The Delphi method identified several key risk factors affecting the Robusta coffee supply chain. The risks identified in this study are categorized into environmental, market, socio-economic, and infrastructural risks to reflect the comprehensive nature of supply chain challenges in the agricultural sector. These categories were chosen because they encompass the most critical areas that influence supply chain performance, from unpredictable environmental conditions (e.g., climate change) to market fluctuations, socio-economic factors affecting labor availability, and the physical infrastructure required for efficient product transportation. These categories also align with previous studies on agricultural risk assessment, providing a well-rounded framework for evaluating risks. The primary risks identified include:

- Environmental Risks: Climate variability, extreme weather events, pest and disease outbreaks.
- Market Risks: Price fluctuations, demand variability.
- Socio-economic Risks: Labor shortages, socio-political instability.
- Infrastructural Risks: Inadequate infrastructure, transportation disruptions.

Fuzzy FMEA implementation: The fuzzy FMEA methodology was validated using historical data on past risk occurrences in the Robusta coffee supply chain, ensuring that the model accurately reflects real-world conditions. This validation process is crucial, as it confirms that the fuzzy model is not only theoretical but also practical and grounded in actual risk events. By comparing the model's risk priority numbers (RPN) with historical data, we can assess the model's accuracy in prioritizing risks that have historically impacted the supply chain. The fuzzy models' results were compared with historical data on risk occurrences and impacts in the Robusta coffee supply chain to ensure their validity and applicability.

Calculation nof fuzzy risk priority number (RPN)

The defuzzification process, specifically using the centroid method, was employed to convert fuzzy values into crisp outputs. The fuzzy RPN for each risk was calculated using the formula:

$$Fuzzy\ RPN = Fuzzy\ S \times Fuzzy\ O \times Fuzzy\ D$$

The fuzzy RPN values were then defuzzified to obtain crisp values for comparison. Defuzzification was done using the centroid method. The centroid method was chosen because it provides the most balanced representation of fuzzy data by calculating the center of gravity of the fuzzy set. This process is critical for decision-making, as it allows for clear, actionable insights from complex fuzzy data, enabling supply chain managers to make informed decisions based on quantified risks.

Table 3: *RPN calculation.*

Risk factor	Severity (S)	Occurrence (O)	Detection (D)	Fuzzy RPN (TFNs)	Defuzzified (RPN)
Climate Variability	High (7, 8, 9)	Likely (7, 8, 9)	Moderate (4, 5, 6)	(196, 360, 486)	347.33
Price Fluctuations	High (7, 8, 9)	Possible (4, 5, 6)	Moderate (4, 5, 6)	(112, 240, 324)	225.33
Labor Shortages	Medium (4, 5, 6)	Possible (4, 5, 6)	Difficult (7, 8, 9)	(112, 240, 486)	279.33
Inadequate infrastructure	Medium (4, 5, 6)	Likely (7, 8, 9)	Difficult (7, 8, 9)	(196, 360, 486)	347.33

Source: *Primary Data Processed (2024).*

Fuzzy FMEA results: The Table 3 summarizes the fuzzy RPN calculations for key risks.

The Risk Priority Number (RPN) calculations for the Robusta coffee supply chain highlight the severity, occurrence, and detection difficulties associated with various risk factors. The fuzzy RPN values, expressed as Triangular Fuzzy Numbers (TFNs), and their defuzzified RPN values provide insights into the relative importance of each risk factor. Climate variability is identified as a highly severe risk that is likely to occur and moderately difficult to detect, with a defuzzified RPN of 347.33. This indicates a substantial impact on the supply chain, necessitating immediate and significant mitigation efforts. Climate variability and inadequate infrastructure emerged as the top two risks. Climate variability, such as unpredictable rainfall patterns and rising temperatures, directly impacts coffee yield and quality, leading to reduced productivity and financial losses for farmers. Price fluctuations also present a high-severity risk but are less likely to occur compared to climate variability and are moderately difficult to detect.

The defuzzified RPN for price fluctuations is 225.33, suggesting it is a significant but lower priority risk than climate variability and inadequate infrastructure. Inadequate infrastructure, including poor road networks and limited access to storage facilities, exacerbates these challenges by increasing transportation costs and leading to delays, further undermining supply chain efficiency. These risks underscore the urgent need for mitigation strategies to protect the resilience of the Robusta coffee supply chain. Labour shortages pose a medium-severity risk with a possibility of occurrence and are difficult to detect. With a defuzzified RPN of 279.33, labour shortages are notable, requiring strategies to address labour availability and conditions within the supply chain. Inadequate infrastructure, identified as a medium severity risk likely to occur and difficult to detect, has a defuzzified RPN of 347.33. This places it on par with climate variability, indicating a critical need for infrastructural improvements to enhance the supply chain's resilience.

Table 4: *Pairwise comparation matrix.*

Criteria	Impact	Cost	Resource availability
Impact	(1, 1, 1)	(1/3, 1, 3)	(1/5, 1/3, 1)
Cost	(1/3, 1, 3)	(1, 1, 1)	(1/3, 1, 3)
Resource availability	(1, 3, 5)	(1/3, 1, 3)	(1, 1, 1)

Source: *Primary data processed (2024).*

Table 5: *Fuzzy AHP results.*

Mitigation strategy	Impact weight	Cost weight	Resource availability weight	Overall weight	Rank
Improved irrigation systems	0.35	0.25	0.20	0.266	2
Diversification of crops	0.30	0.20	0.25	0.250	3
Enhanced pest management	0.25	0.30	0.30	0.283	1
Infrastructure development	0.20	0.25	0.25	0.233	4

Source: *Primary data processed (2024).*

Fuzzy analytical hierarchy process (AHP)

Criteria and sub-criteria definition: The criteria for evaluating mitigation strategies impact, cost, and resource availability are fundamental to ensuring practical implementation (Table 5). For example, impact refers to how significantly a strategy can reduce risks, such as improved irrigation systems addressing water shortages. Cost relates to the financial investment required, with strategies like infrastructure development being capital-intensive. Resource availability considers the accessibility of necessary resources, such as manpower for pest management. Providing these real-world examples helps stakeholders understand how these criteria apply in the context of the Robusta coffee supply chain. The criteria for prioritizing risk mitigation strategies included:

- Impact: The potential effect of the mitigation strategy on reducing the risk.
- Cost: The financial requirement for implementing the strategy.
- Resource Availability: The availability of resources (human, technological, etc.) needed for the strategy.

Fuzzy AHP calculation: The mitigation strategies were ranked based on the calculated fuzzy weights to determine their effectiveness and priority. These strategies encompass several critical areas of improvement. First, improving irrigation systems enhances water efficiency and supports crop resilience. Second, diversification of crops is proposed to reduce dependency on a single crop, thereby minimizing economic risk. Third, enhanced pest management practices are essential for protecting crops from diseases and pests, which can significantly impact yield and quality. Lastly, infrastructure development is crucial for improving the overall efficiency of the supply chain, from transportation to storage facilities. By prioritizing these strategies, the study aims to bolster the robustness and sustainability of the Robusta coffee supply chain in East Java.

The Fuzzy Analytical Hierarchy Process (AHP) results for the mitigation strategies in the Robusta coffee supply chain provide a clear prioritization based on impact, cost, and resource availability weights. According to table 5 the overall weight for each strategy is calculated to determine their respective rankings. Enhanced pest management emerged as the top priority, with the highest overall weight of 0.283. This strategy received significant weights for cost (0.30) and resource availability (0.30), indicating that it is a relatively cost-effective and resource-efficient approach to mitigating risks within the supply chain. Improved irrigation systems were ranked second with an overall weight of 0.266, receiving the highest impact weight (0.35), underscoring its importance in addressing climate variability and ensuring stable coffee production. Diversification of crops, with an overall weight of 0.250, was ranked third. This strategy is highly valued for its resource availability (0.25) and impact (0.30), highlighting its potential to reduce dependency on a single crop and mitigate market risks. Infrastructure development ranked fourth with an overall weight of 0.233, emphasizing the need for physical infrastructure investment to support the supply chain. However, it received relatively lower weights for impact (0.20) and cost (0.25).

Enhanced pest management was ranked the top priority, underscoring the critical need to protect crops from the detrimental effects of pests and diseases, which can severely impact yield and quality. Following closely in priority is the implementation of improved irrigation systems. This strategy aims to optimize water usage, ensuring crops receive adequate hydration even during drought or irregular rainfall. The ranked mitigation strategies align closely with current practices in the Robusta coffee industry in East Java. For instance, enhanced pest management is already a critical focus due to the prevalence of coffee pests such as the coffee berry borer, which has caused significant crop losses in recent years. By ranking pest management as a top priority, this study supports ongoing efforts in the region to safeguard coffee production from these persistent threats. By focusing on these top-ranked strategies, the study highlights the most pressing areas for intervention to strengthen the resilience and productivity of the Robusta coffee supply chain in East Java.

Analysis of fuzzy FMEA

Climate variability emerged as a top risk due to its severe impact on coffee production. Climate variability has been identified as the most critical risk in this study, with significant implications for coffee production. Local case studies, such as the droughts experienced in the Dampit region of East Java in recent years, provide concrete examples of how climate unpredictability has led to substantial yield reductions. Farmers have struggled to adapt to these changes, which have disrupted planting and harvesting schedules, highlighting the need for more resilient agricultural practices. This result includes fluctuations in temperature, irregular rainfall patterns, and extreme weather events, all of which can adversely affect crop yields and quality (Gwambene *et al*., 2023). Temperature fluctuations can disrupt coffee plants flowering and fruiting cycles, leading to reduced yields (Kath *et al*., 2023). Irregular rainfall patterns can cause water stress, affecting plant health and productivity, while excessive rainfall can lead to soil erosion and nutrient leaching (Talukder *et al*., 2021; Vanden and Centinari, 2021). Extreme weather events, such as storms and floods, can cause physical damage to coffee plants and infrastructure, further impacting production.

The fuzzy FMEA results underscore the need for robust strategies to mitigate climate-related risks (Nakhaei *et al*., 2023). Implementing climate-resilient farming practices is crucial (Viswanathan *et al*., 2020). These practices include selecting and cultivating coffee plant varieties more tolerant to temperature and moisture variability. Adopting agroforestry techniques, which integrate trees into coffee plantations, can provide shade, reduce temperature extremes, and improve soil moisture retention (de Carvalho *et al*., 2021). Improving irrigation systems is another fundamental strategy. Efficient irrigation methods, such as drip irrigation, can ensure that coffee plants receive adequate water even during periods of drought (Byrareddy *et al*., 2021). Rainwater harvesting systems can capture and s tore rainfall during dry spells, helping maintain consistent soil moisture levels (Chipomho *et al*., 2024). By addressing the multifaceted challenges posed by climate variability, these strategies can enhance the resilience and sustainability of coffee production in East Java.

Inadequate infrastructure was also a critical risk in the Robusta coffee supply chain. The discussion on infrastructure could be enhanced by suggesting specific actions that local authorities and supply chain stakeholders can take. For instance, improving road networks in remote coffee-growing regions would facilitate more efficient transportation, reducing delays and product spoilage. Additionally, the construction of centralized storage facilities could help farmers store their coffee beans securely, ensuring better quality control and reducing losses during transportation. The lack of proper roads, storage facilities, and processing plants can lead to inefficiencies and increased post-harvest losses (Yeshiwas and Tadele, 2021). Road conditions need to improve the timely transportation of coffee beans from farms to processing units, causing delays that can affect the freshness and quality of the produce (Li *et al*., 2023). Inadequate storage facilities exacerbate this problem by failing to provide optimal conditions for preserving coffee beans, leading to spoilage and loss of quality (Balehegn *et al*., 2022). Furthermore, insufficient processing plants limit the capacity for timely and efficient processing of harvested beans, which can result in bottlenecks and further degradation of product quality.

This result highlights the necessity for substantial investment in infrastructure development to enhance the efficiency and reliability of the supply chain. Improving road networks will facilitate faster and more reliable transportation, reducing delays and maintaining the quality of coffee beans (Uygun and Jafri, 2020). Developing advanced storage facilities equipped with climate control can help preserve the quality of harvested beans by protecting them from adverse environmental conditions. Additionally, expanding processing plants' capacity and technological capabilities can ensure that coffee beans are processed promptly and efficiently, maintaining their quality and market value.

While market risks such as price fluctuations (defuzzified RPN: 225.33) and socio-economic risks like labor shortages (defuzzified RPN: 279.33) were not ranked as high as environmental and infrastructural risks, they still pose significant challenges. Price volatility affects farmers' income stability, and labor shortages can hinder timely harvesting and processing of coffee beans. Addressing these risks requires economic strategies to stabilize market prices and policies to improve labor availability and conditions.

Analysis of Fuzzy AHP

Enhanced pest management is ranked as the top priority due to the severity of pest-related risks in East Java. Enhanced pest management ranked highest in the Fuzzy AHP analysis, with an overall weight of 0.283. This strategy is crucial given the susceptibility of coffee plants to various pests and diseases, which can drastically reduce yields and quality. Coffee farmers in this region have reported frequent infestations by pests like the coffee leaf rust and berry borer, which can devastate entire crops. The recent outbreaks of these pests, combined with the limited availability of effective pest control measures, make this strategy critical for maintaining production levels. Pest management is thus prioritized over irrigation improvements because it addresses an immediate and persistent threat to coffee yields. Implementing integrated pest management practices and using pest-resistant coffee varieties can mitigate this risk effectively.

Improved irrigation systems were the second-highest priority, with an overall weight of 0.266. Efficient irrigation is vital for coping with the irregular rainfall patterns caused by climate variability. Technologies such as drip irrigation and rainwater harvesting can help maintain optimal soil moisture levels, thereby enhancing crop resilience.

Crop diversification is well-documented as a risk mitigation strategy, but additional context on its economic impact in East Java can strengthen the argument. Diversified crops provide farmers with alternative revenue streams, reducing their reliance on a single crop and spreading economic risk. For example, intercropping coffee with other high-value crops such as pepper or cacao has been shown to increase farm incomes and enhance resilience against market fluctuations, making it an economically beneficial strategy. Diversification of crops was ranked third, with an overall weight of 0.250. Diversifying crops can reduce dependency on coffee and spread the risk associated with market and environmental fluctuations. This strategy can also provide additional income streams for farmers, enhancing their economic resilience.

Infrastructure development was ranked fourth, with an overall weight of 0.233. Despite being a lower priority compared to other strategies, it remains essential for the long-term sustainability of the supply chain. Developing better roads, storage facilities, and processing plants can significantly reduce post-harvest losses and improve overall supply chain efficiency.

Implications for supply chain resilient

Integrating fuzzy logic into FMEA and AHP provided a robust framework for handling risk analysis and decision-making uncertainties and complexities. This approach enabled a more nuanced understanding of the risks and the prioritization of mitigation strategies based on multiple criteria. The findings of this study have significant implications for various stakeholders in the Robusta coffee supply chain. Farmers can adopt climate-resilient and integrated pest management practices to mitigate environmental risks. For policymakers, the insights can guide the formulation of policies that support infrastructure development and climate-resilient farming practices. For farmers, the research highlights practical strategies to enhance resilience, such as adopting pest management techniques and diversifying crops. Supply chain managers can use the fuzzy model to prioritize investments in infrastructure and technology that strengthen the overall supply chain. This study contributes to the supply chain risk management field by demonstrating the applicability of fuzzy logic techniques in a real-world agricultural context. It showcases how fuzzy FMEA and AHP can effectively assess and mitigate risks, providing a model that can be adapted to other agricultural supply chains facing similar challenges.

Conclusions and Recommendations

This study sought to improve risk analysis and mitigation strategies within the Robusta coffee supply chain in East Java by employing fuzzy logic methodologies. Through the integration of Fuzzy Failure Mode and Effects Analysis (FMEA) and Fuzzy Analytical Hierarchy Process (AHP), a robust framework was established to identify, evaluate, and prioritize risks and mitigation strategies amidst uncertainty. The study identified key risks, with climate variability and inadequate infrastructure emerging as the highest priority, both of which have a substantial impact on the supply chain's resilience. The prioritization of mitigation strategies revealed that enhanced pest management, improved irrigation systems, crop diversification, and infrastructure development are the most effective solutions for addressing these risks. Additionally, actionable recommendations were provided for farmers, policymakers, and supply chain managers to strengthen the resilience and sustainability of the Robusta coffee supply chain. The study applied fuzzy logic techniques, specifically FMEA and AHP to assess and prioritize risks in the Robusta coffee supply chain in East Java. The results highlight that the most critical risks include climate variability, pest and disease outbreaks, and infrastructure limitations. Based on these findings, the most effective mitigation strategies are improved pest control practices, investment in irrigation systems, crop diversification, and rural infrastructure development. It is recommended that policymakers focus on climate-resilient agricultural programs, while supply chain managers and cooperatives should invest in targeted training and technology adoption to reduce vulnerability. Further research could explore the integration of dynamic data-driven models to complement fuzzy approaches in real-time decision-making.

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Novelty Statement

This study introduces the integration of Fuzzy Failure Mode and Effects Analysis (FMEA) and Fuzzy Analytical Hierarchy Process (AHP) for risk prioritization and mitigation in the Robusta coffee supply chain. Unlike prior research, this approach addresses the inherent uncertainty and complexity of agricultural supply chains, offering a novel, data-driven framework for improving supply chain resilience in the face of environmental and infrastructural risks.

Author's Contribution

Wahyu Lis Setyaningsih: Contributed to the design of the study, data collection, and analysis. Drafted the initial manuscript and revised it critically for important content.
Budi Setiawan: Assisted with data analysis, particularly the Monte Carlo simulation, and contributed to refining the methodology section. Also helped revise the manuscript for accuracy.
Agustina Shinta: Provided guidance on the theoretical framework and ensured the correct application of fuzzy logic techniques. Reviewed and revised the manuscript before final submission.

Generative AI and AI-assisted technology statement
The authors declare that no generative AI or AI-assisted technology was used in the writing or editing of this manuscript.

Conflict of interest
The authors have declared no conflict of interest.

References

Balehegn, M., A. Ayantunde, T. Amole, D. Njarui, B.D. Nkosi, F.L. Müller, R. Meeske, T.J. Tjelele, I.M. Malebana, O.R. Madibela, W.S. Boitumelo, B. Lukuyu, A. Weseh, E. Minani and A.T. Adesogan. 2022. Forage conservation in sub- Saharan Africa: Review of experiences, challenges, and opportunities. Agron. J., 114(1): 75–99. https://doi.org/10.1002/agj2.20954

Byrareddy, V., L. Kouadio, S. Mushtaq, J. Kath and R. Stone. 2021. Coping with drought: Lessons learned from robusta coffee growers in Vietnam. Clim. Ser., 22: 100229. https://doi.org/10.1016/j.cliser.2021.100229

Campbell, D., 2021. Environmental change and the livelihood resilience of coffee farmers in Jamaica: A case study of the Cedar Valley farming region. J. Rural Stud., 81: 220–234. https://doi.org/10.1016/j.jrurstud.2020.10.027

Chipomho, J., C. Moreblessing, F. Makore and P. Cosmas. 2024. Rainwater harvesting technologies and soil moisture conservation in marginalised semi-arid soils of Southern Africa. In; The marginal soils of Africa. Springer Nature Switzerland. pp. 361–375. https://doi.org/10.1007/978-3-031-55185-7_19

de Carvalho, A.F., E.I. Fernandes-Filho, M. Daher, L.C. Gomes, I.M. Cardoso, R.B.A. Fernandes and C.E.G.R. Schaefer. 2021. Microclimate and soil and water loss in shaded and unshaded agroforestry coffee systems. Agrof. Syst., 95(1): 119–134. https://doi.org/10.1007/s10457-020-00567-6

Deiva Ganesh, A. and P. Kalpana. 2022. Future of artificial intelligence and its influence on supply chain risk management. A systematic review. Comput. Ind. Eng., 169: 108206. https://doi.org/10.1016/j.cie.2022.108206

Erdoğan, M., 2022. Assessing farmers perception to Agriculture 4.0 technologies: A new interval-valued spherical fuzzy sets based approach. Int. J. Intell. Syst., 37(2): 1751–1801. https://doi.org/10.1002/int.22756

Gurtu, A. and J. Johny. 2021. Supply chain risk management: Literature review. Risks, 9(1): 16. https://doi.org/10.3390/risks9010016

Gwambene, B., E. Liwenga and C. Mung'ong'o. 2023. Climate change and variability impacts on agricultural production and food security for the smallholder farmers in Rungwe, Tanzania. Environ. Manage., 71(1): 3–14. https://doi.org/10.1007/s00267-022-01628-5

Hochachka, G., 2023. Climate change and the transformative potential of value chains. Ecol. Econ., 206: 107747. https://doi.org/10.1016/j.ecolecon.2023.107747

Jawo, T.O., D. Kyereh and B. Lojka. 2023. The impact of climate change on coffee production of small farmers and their adaptation strategies: A review. Clim. Dev., 15(2): 93–109. https://doi.org/10.1080/17565529.2022.2057906

Kath, J., V.M. Byrareddy, A. Craparo, T. Nguyen-Huy, S. Mushtaq, L. Cao and L. Bossolasco. 2020. Not so robust: Robusta coffee production is highly sensitive to temperature. Glob. Change Biol., 26(6): 3677–3688. https://doi.org/10.1111/

gcb.15097

Kath, J., V.M. Byrareddy, K. Reardon-Smith and S. Mushtaq. 2023. Early flowering changes robusta coffee yield responses to climate stress and management. Sci. Total Environ., 856: 158836. https://doi.org/10.1016/j.scitotenv.2022.158836

Kindo, A.A., G. Kaladzavi, S. Malo, G. Camara, T.M.Y. Tapsoba and Kolyang. 2020. Fuzzy logic approach for knowledge modeling in an Ontology: A review. 2020 IEEE 2nd Int. Conf. Smart Cities Commun., pp. 1–8. https://doi.org/10.1109/SCCIC51516.2020.9377335

Li, K., J.Y. Lee and A. Gharehgozli. 2023. Blockchain in food supply chains: A literature review and synthesis analysis of platforms, benefits and challenges. Int. J. Prod. Res., 61(11): 3527–3546. https://doi.org/10.1080/00207543.2021.1970849

Maskrey, S.A., N.J. Mount and C.R. Thorne. 2022. Doing flood risk modelling differently: Evaluating the potential for participatory techniques to broaden flood risk management decision- making. J. Flood Risk Manage., 15(1). https://doi.org/10.1111/jfr3.12757

Nakhaei, M., P. Nakhaei, M. Gheibi, B. Chahkandi, S. Wacławek, K. Behzadian, A.S. Chen and L.C. Campos. 2023. Enhancing community resilience in arid regions: A smart framework for flash flood risk assessment. Ecol. Indicat., 153: 110457. https://doi.org/10.1016/j.ecolind.2023.110457

Olufunke O., F.A. Ajayi, C.A. Udeh and O.A. Odejide. 2024. Risk management and HR practices in supply chains: Preparing for the future. Magna Sci. Adv. Res. Rev., 10(2): 238–255. https://doi.org/10.30574/msarr.2024.10.2.0065

Pancsira, J., 2022. International coffee trade: A literature review. J. Agric. Inf., 13(1). https://doi.org/10.17700/jai.2022.13.1.654

Reyes-García, C.A. and A.A. Torres-García. 2022. Fuzzy logic and fuzzy systems. In: Biosignal processing and classification using computational learning and intelligence. Elsevier. pp. 153–176. https://doi.org/10.1016/B978-0-12-820125-1.00020-8

Ruhyana, N.F., M. Mardianis, H. Roseline and S.N. Wulandari. 2022. Value chain and competitiveness of manglayang timur java preanger arabica coffee. J. Ekon. Dan Kebijakan Publ., 13(1): 43–56. https://doi.org/10.22212/jekp.v13i1.1932

Shanker, S., H. Sharma and A. Barve. 2022. Analysing the critical success factors and the risks associated with third-party logistics in the food supply chain: A case of coffee industry. J. Adv. Manage. Res., 19(2): 161–197. https://doi.org/10.1108/JAMR-11-2020-0307

Talukder, B., N. Ganguli, R. Matthew, G.W. vanLoon, K.W. Hipel and J. Orbinski. 2021. Climate <scp>change- triggered</scp> land degradation and planetary health: A review. Land Degrad. Dev., 32(16): 4509–4522. https://doi.org/10.1002/ldr.4056

Uygun, Y. and S.A.I. Jafri. 2020. Controlling risks in sea transportation of cocoa beans. Cogent Bus. Manage., 7(1): 1778894. https://doi.org/10.1080/23311975.2020.1778894

Vanden, H.J. and M. Centinari. 2021. Under-vine vegetation mitigates the impacts of excessive precipitation in vineyards. Front. Plant Sci., pp. 12. https://doi.org/10.3389/fpls.2021.713135

Viswanathan, P.K., K. Kavya and C.S. Bahinipati. 2020. Global patterns of climate-resilient agriculture: A review of studies and imperatives for empirical research in India. Rev. Dev. Change, 25(2): 169–192. https://doi.org/10.1177/0972266120966211

Voora, V., S. Bermúdez, C. Larrea and S. Baliño. 2019. Global Market Report: Coffee.

Yeshiwas, Y. and E. Tadele. 2021. An investigation into major causes for postharvest losses of horticultural crops and their handling practice in Debre Markos, North-Western Ethiopia. Adv. Agric., 2021: 1–10. https://doi.org/10.1155/2021/198530

Zadeh, L.A., 1965. Fuzzy sets. Information and Control, 8(3): 338–353. https://doi.org/10.1016/S0019-9958(65)90241-X