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Risk Mitigation Strategies for Raw Material Supply in the Animal Feed Industry in Response to Climate Change

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Abstract

Background: The animal feed industry is highly dependent on agricultural raw materials such as corn, rice bran, and fine bran, which account for approximately 85–90% of total production costs. Climate change in Indonesia, characterized by unpredictable rainfall patterns and extreme weather conditions, increases supply chain risks by adversely affecting agricultural productivity.
Objective: This study aims to identify and assess supply chain risks at PT XYZ associated with climate change. Specifically, it seeks to formulate evidence-based mitigation strategies to enhance supply chain resilience in the animal feed industry.
Methods: This research was conducted during the first quarter of 2025 using both primary and secondary data. The analysis integrated the Supply Chain Operations Reference (SCOR), *House of Risk* (HOR), and Analytical Hierarchy Process (AHP) methods.
Results: The findings indicate that climate variability significantly affects raw material availability, price volatility, and supply sustainability. The proposed mitigation strategies include supplier diversification, safety stock management, and the strengthening of risk monitoring systems.
Conclusion: These strategies are expected to improve supply chain resilience in the animal feed industry.

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INTRODUCTION

The animal feed industry plays a strategic role in supporting the development of the livestock sector in Indonesia, particularly in ensuring the availability of high-quality feed as a key factor in improving livestock productivity (Khanal et al., 2022; Nuraeni et al., 2025; Wattie et al., 2024). The existence of this industry not only functions as the backbone of the livestock sector but also contributes significantly and indirectly to national food security (Michalk et al., 2019; Mukesh et al., 2022). The stable availability of high-quality feed is a crucial factor in maintaining the sustainability of animal protein production, which is one of the basic needs of society (Kim et al., 2019; Rauw et al., 2023; Van Huis & Oonincx, 2017).

Specifically, in its cost structure, primary raw materials such as corn, rice bran, and fine bran account for approximately 85–90% of total production costs. This condition indicates that the sustainability of the animal feed industry is highly dependent on the availability, stability, and quality of these raw materials (Halmemies-Beauchet-Filleau et al., 2018; Pexas et al., 2023). The high dependence on agricultural commodities makes this industry highly sensitive to environmental changes, particularly those related to climate dynamics (Porfirio et al., 2018).

The strong reliance on agriculture-based raw materials makes the animal feed industry highly vulnerable to climate change (Higuita et al., 2023; Uddin & Kebreab, 2020). Climate change, characterized by fluctuations in rainfall, rising temperatures, and the increasing frequency of extreme weather events such as floods and droughts, has a significant impact on agricultural productivity (Change, 2001). These impacts not only affect the quantity of harvests but also create uncertainty in agricultural production patterns, which are seasonal and difficult to predict.

Empirical data from BPS (2023) indicate that national corn production fell by 7.3% during the 2022–2023 El Niño drought, while BMKG (2023) recorded a 40% increase in extreme weather events affecting agricultural zones over the past five years. In the animal feed sector specifically, GPMT (2023) reported that 62% of member companies experienced raw material supply disruptions of more than two weeks during the peak of the 2022 dry season, with average production losses estimated at 15–20% of planned monthly output.

This uncertainty directly leads to instability in the supply of raw materials for the animal feed industry. Under normal conditions, the raw material supply chain can be planned relatively steadily. However, under increasingly unpredictable climate conditions, companies face high supply fluctuations, both in terms of volume and timing of availability. This situation results in increased volatility in raw material prices, delivery delays, and disruptions in production planning. In the long term, these conditions may reduce operational efficiency, increase production costs, and potentially lead to failures in meeting market demand on time.

Internal supply chain records of PT XYZ for Q1 2025 indicate that weather-related supply delays averaged 8.4 days per event, with the most severe disruption reaching 21 days during the January 2025 flooding in key corn-producing regions. This compares to a baseline average delay of 2.1 days under normal weather conditions, representing a fourfold increase in delay duration attributable to climate-related disruptions. The frequency of delay events also increased from an average of 1.2 incidents per month in 2023 to 3.7 incidents per month in Q1 2025.

In addition to affecting quantity, climate change also significantly impacts the quality of raw materials. High temperature and humidity conditions can increase the risk of mycotoxin contamination in corn, which may reduce the quality and safety of feed raw materials (Coradi et al., 2025). The decline in raw material quality not only affects the production process but may also influence the quality of the final product and the performance of livestock consuming the feed. Thus, the risks faced are not only operational but may also affect the company's reputation and competitiveness.

On the other hand, climate change also disrupts distribution systems through infrastructure damage caused by flooding and transportation disruptions resulting from extreme weather. These conditions increase the risk of delays in raw material deliveries, further exacerbating uncertainty in the supply chain. Therefore, climate change can be viewed as a systemic external risk source because it affects all stages of the supply chain, from upstream production to downstream distribution.

As a company operating in the animal feed industry, PT XYZ faces various challenges in maintaining the stability of its supply chain. These challenges include a high dependence on certain suppliers, limited diversification of raw material sources, and suboptimal risk mitigation systems. In addition, the imbalance between demand and supply influenced by climate disruptions further increases the company's vulnerability to operational risks.

These conditions indicate that the supply chain risks faced by PT XYZ are not only operational but also strategic in nature and influenced by external factors that are difficult to control. Therefore, a systematic, integrated, and data-driven approach is required to identify, analyze, and manage these risks so that the company can enhance its supply chain resilience in dealing with environmental uncertainties.

Based on these issues, this study aims to identify raw material supply risks resulting from climate change, assess the level of risk faced, and formulate effective and applicable mitigation strategies to improve the company's supply chain resilience in responding to increasingly complex and uncertain environmental dynamics.

Literature Review

Climate change is one of the external factors that significantly affects supply chain performance, particularly in sectors that heavily depend on agricultural outputs (IPCC, 2021). This phenomenon is characterized by changes in rainfall patterns, rising global temperatures, and the increasing frequency of extreme weather events such as floods and droughts. Increasing climate variability leads to greater uncertainty in food production systems, both in terms of the quantity and quality of harvests. This condition directly impacts the instability of raw material supply for agriculture-based industries, including the animal feed industry, which relies heavily on the continuity and quality of agricultural production.

Climate change affects not only productivity but also the quality of raw materials. Change (2001) explains that changes in environmental conditions can lead to a decline in nutritional quality and an increased risk of crop damage. In the context of supply chains, these conditions result in a higher risk of supply disruptions, commodity price volatility, and uncertainty in production planning. This uncertainty not only affects operational performance but also influences cost efficiency and a company's ability to meet market demand in a timely manner. Therefore, climate change can be viewed as a systemic source of risk that affects all elements of the supply chain, from upstream to downstream.

In response to these conditions, the implementation of supply chain risk management becomes crucial. Supply chain risk management is a systematic approach that includes the processes of identifying, analyzing, evaluating, and controlling risks that may disrupt company operations. Zsidisin (2003) states that effective risk management not only minimizes losses but also enhances supply chain resilience against external disruptions. Furthermore, Chopra (2004) emphasize that risks in supply chains are multidimensional, originating from supply disruptions, demand fluctuations, operational failures, as well as external factors such as climate change. Therefore, companies need adaptive capabilities to manage dynamic and unpredictable risks.

The complex and interconnected nature of supply chain risks requires a structured and integrated approach to risk management. One approach used to map supply chain activities is the Supply Chain Operations Reference (SCOR) model. This model was developed by the Supply Chain Council and classifies supply chain activities into five main processes: plan, source, make, deliver, and return. The SCOR model functions not only as a process-mapping tool but also as a framework that helps companies identify critical points that may pose risks at each stage of the supply chain.

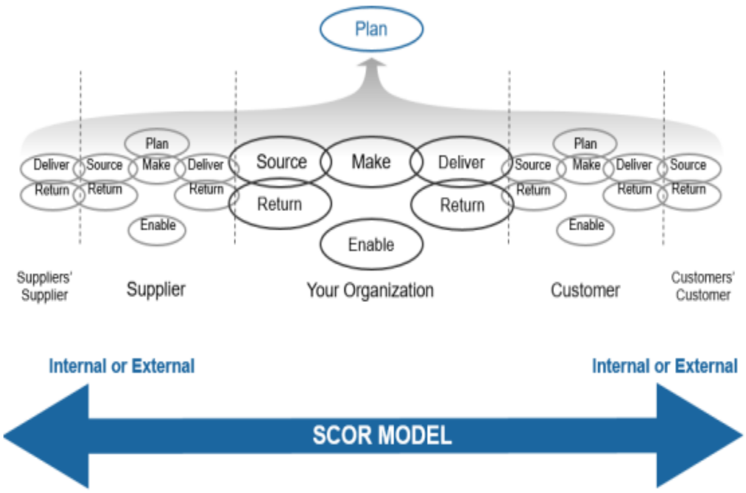

Figure 1. SCOR Model [5]

Figure 1 illustrates that all supply chain activities are interconnected and form an integrated system with interdependencies. Disruptions occurring in one process can affect other processes, thereby reinforcing the importance of a systemic approach to risk management. In this context, the SCOR model helps companies understand the interrelationships among processes and identify potential risks more comprehensively.

The SCOR model can be further elaborated into more detailed process levels through the decomposition of operational activities. This decomposition includes planning processes (P1–P5), sourcing (Source; S1–S3), production (Make; M1–M3), and distribution (Deliver; D1–D3), enabling a more in-depth analysis of risk sources and their linkages to the company's operational activities.

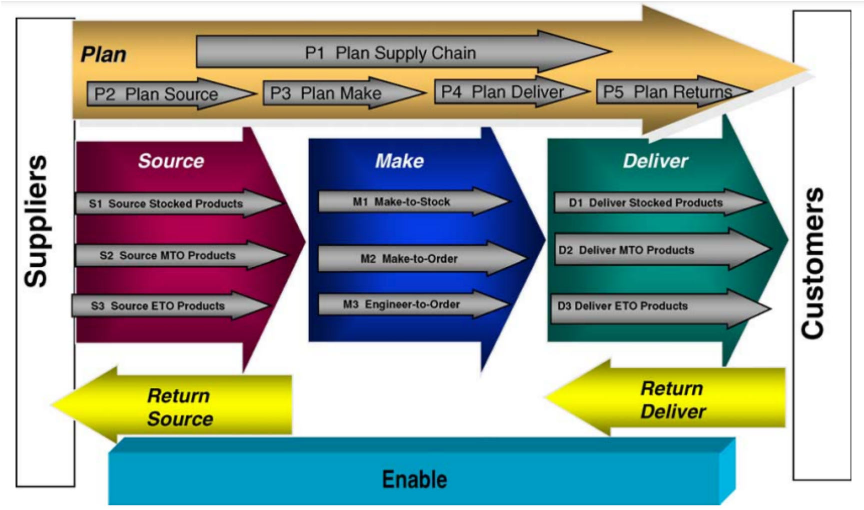

Figure 2. SCOR Model Process Decomposition

Figure 2 presents a detailed breakdown of activities within each SCOR process, which can be used as a basis for identifying risk events at every stage of the supply chain. Thus, the SCOR model not only serves as a mapping tool but also as a foundation for a systematic and structured risk identification process.

In the process of identifying and prioritizing risks, the House of Risk (HOR) method is used as an effective approach. This method was introduced by Nyoman (2009), integrating risk management concepts with the Failure Mode and Effects Analysis (FMEA) approach. HOR has the advantage of identifying the relationship between risk events and risk agents, enabling companies to focus on the most dominant sources of risk. Through the calculation of Aggregate Risk Priority (ARP), this method quantitatively measures the level of risk priority, thereby facilitating the determination of the most effective mitigation strategies.

At the next stage, the Analytic Hierarchy Process (AHP) method is used to support decision-making in determining the priority of mitigation strategies. This method, developed by Saaty (1980), applies a pairwise comparison approach to generate priority weights based on specific criteria. The strength of AHP lies in its ability to accommodate multiple decision criteria simultaneously, such as effectiveness, cost, resource availability, and the suitability of strategies to company conditions. Thus, the resulting decisions become more rational, systematic, and accountable.

Conceptually, the integration of the SCOR model, the House of Risk (HOR) method, and the Analytic Hierarchy Process (AHP) provides a comprehensive approach to supply chain risk management. SCOR functions as a process mapping tool, HOR as a tool for risk identification and prioritization, and AHP as a decision-making tool. The combination of these three methods enables a thorough risk analysis, from identification to the determination of optimal mitigation strategies.

Therefore, climate change not only affects production aspects but also influences the entire supply chain system, from raw material procurement to the distribution of final products. Consequently, an integrated, adaptive, and data-driven risk management approach is required to enhance supply chain resilience in dealing with uncertainties caused by climate change.

Although numerous studies have discussed supply chain risk management, most still focus on partial risk identification or employ a single-method approach in their analyses. Some studies use the SCOR model to map supply chain processes but have not deeply linked it with quantitative risk prioritization analysis. On the other hand, the House of Risk (HOR) method has been widely used to identify and prioritize risks, but it is generally not integrated with a systematic process mapping approach such as SCOR.

Furthermore, the use of the Analytic Hierarchy Process (AHP) in previous studies tends to be limited to decision-making without directly linking it to the results of structured risk analysis. This indicates that there are still limitations in integrating methods that can connect process mapping, risk identification, and the determination of mitigation strategies within a comprehensive analytical framework.

In addition, studies on supply chain risks due to climate change in the animal feed industry remain relatively limited, particularly in the context of developing countries such as Indonesia. Most studies focus on the agricultural sector in general, without specifically examining its impact on downstream industries such as animal feed, which have a high dependency on agricultural raw materials.

Based on these conditions, there is a research gap in developing an integrated approach that connects the SCOR model as a process mapping tool, the HOR method as a risk identification and prioritization tool, and AHP as a decision-making tool for determining optimal mitigation strategies. Moreover, research is needed that specifically examines the impact of climate change on supply chain risks in the animal feed industry in order to provide both theoretical and practical contributions.

Therefore, this study seeks to address this gap by integrating the SCOR model, the House of Risk (HOR) method, and the Analytic Hierarchy Process (AHP) into a comprehensive analytical framework to identify, analyze, and formulate mitigation strategies for supply chain risks caused by climate change in the animal feed industry.

METHOD

This study was conducted at PT XYZ, a company operating in the animal feed industry in Indonesia, with the research period covering the first quarter of 2025. The research location was selected using purposive sampling based on four explicit criteria: (1) the company operated primarily in the animal feed industry with an annual procurement volume exceeding 50,000 tonnes of agricultural raw materials; (2) the supply chain involved multiple suppliers across at least three provinces, reflecting geographic complexity and climate exposure diversity; (3) the company had experienced documented supply disruptions attributable to climate-related events during the 2023–2025 period; and (4) management was willing to provide access to internal supply chain data and key informants. PT XYZ satisfied all four criteria, based on the consideration that the company had a high level of complexity in its agriculture-based raw material supply chain and faced significant risks due to climate change. These conditions made PT XYZ a relevant object for comprehensively examining supply chain risks, particularly those related to environmental uncertainty.

This study employed two types of data: primary data and secondary data. Primary data were obtained through in-depth interviews with individuals holding strategic roles in supply chain management, such as supply chain managers, procurement staff, and operational personnel. Questionnaires were used to obtain quantitative assessments of risk parameters, such as severity, occurrence, and the relationships among risk variables. A total of 12 respondents participated in the quantitative assessment phase, comprising 3 supply chain managers (average experience: 8.2 years), 4 procurement staff members (average experience: 5.6 years), 3 operational supervisors (average experience: 6.1 years), and 2 quality control officers (average experience: 4.8 years). All respondents had direct operational involvement in the supply chain activities under study and were selected based on competence verification through structured pre-screening interviews.

The study adopted a quantitative approach with an integrated analytical method that combined the Supply Chain Operations Reference (SCOR) model, the House of Risk (HOR) method, and the Analytic Hierarchy Process (AHP). This approach was chosen because it could accommodate the multidimensional and interrelated nature of supply chain risks.

The initial stage of the study involved the use of the SCOR model to map the company's supply chain activities into five main processes: plan, source, make, deliver, and return (Chen et al., 2006). This mapping aimed to provide a comprehensive overview of supply chain process flows and to identify potential risk events at each stage. Through this approach, risk identification was conducted systematically and was not limited to a specific part but encompassed the entire supply chain system.

Subsequently, the House of Risk (HOR) method was used to identify and analyze risks in greater depth. In HOR Phase I, risk events and risk agents were identified, followed by an assessment of severity, occurrence, and the relationships between them to obtain the Aggregate Risk Priority (ARP) value (Nyoman Pujawan & Geraldin, 2009). The ARP value served as the basis for determining the priority of risk agents that had the most significant impact on supply chain performance. This approach enabled the company to focus on the most critical sources of risk.

In the next stage, namely HOR Phase II, mitigation strategies were developed for the prioritized risk agents. Each preventive action was evaluated based on its effectiveness in reducing risk and the level of difficulty associated with its implementation. The evaluation results were then used to calculate the Effectiveness-to-Difficulty (ETD) ratio, which served as the basis for determining the most optimal mitigation strategy priorities. This approach considered not only effectiveness but also implementation aspects, resulting in strategies that were more realistic and applicable.

To support the decision-making process in determining the most optimal mitigation strategies, the Analytic Hierarchy Process (AHP) method was employed. This method assigned priority weights to alternative mitigation strategies based on several criteria, such as effectiveness, cost, resource availability, and strategy suitability, using a pairwise comparison approach (Saaty, 1980). In addition, the consistency of judgments in AHP was tested using the Consistency Ratio (CR), where a CR value of ≤ 0.1 indicated that the respondents' judgments were within an acceptable level of consistency. This was important to ensure the validity of the decision-making results.

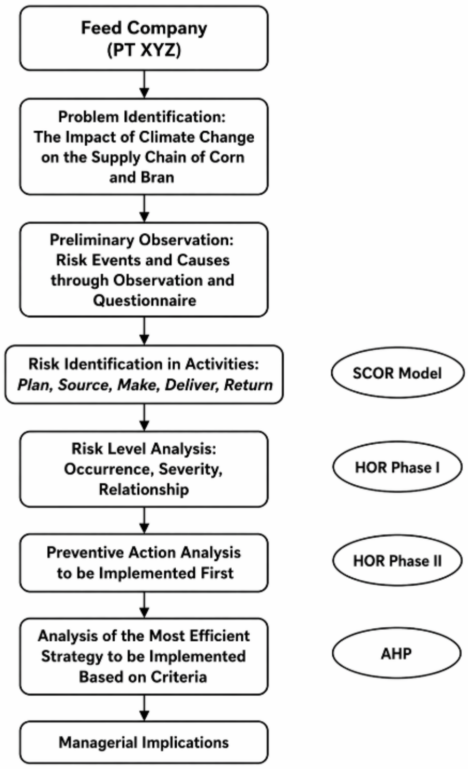

Figure 3. Research Methodology Flow

Figure 3 illustrates the research flow, which began with mapping supply chain processes using SCOR, followed by risk identification and analysis using the HOR Phase I and Phase II methods, and concluded with determining mitigation strategy priorities using the AHP method.

The integrative approach used in this study allowed for a comprehensive risk analysis, from identifying risk sources to determining optimal mitigation strategies. This was important considering the complex and interconnected nature of supply chain risks, which were also influenced by external factors such as climate change that are dynamic and difficult to predict.

Furthermore, the integration of these three methods provided a comparative advantage over the use of a single method, as it combined process mapping (SCOR), risk quantification (HOR), and multi-criteria decision-making (AHP). Thus, the results of this study were not only analytical but also practical and relevant in supporting the company's strategic decision-making, particularly in enhancing supply chain resilience.

Methodological advantages over single-method approaches were also identified. Studies using SCOR alone identified risk locations but lacked probabilistic quantification for prioritization (Nyoman Pujawan & Geraldin, 2009). Studies using HOR alone quantified risk agents but could not provide structured criteria-based strategy selection. Studies using AHP alone enabled multi-criteria decision-making but required structured risk input that AHP itself could not generate without prior HOR analysis. The sequential SCOR → HOR → AHP framework used in this study produced a more robust, traceable, and comprehensive analytical output than any single-method approach could provide, ensuring that risk identification, prioritization, and strategy selection were methodologically coherent and mutually reinforcing.

RESULTS AND DISCUSSION

Results

Risk Identification

Based on the results of risk identification using the Supply Chain Operations Reference (SCOR) approach, it was found that the main risks faced by PT XYZ in the supply of corn and rice bran are dominated by external factors, particularly climate change. This factor directly affects the availability, quality, and timeliness of raw material supplies, which serve as the primary inputs in the production process.

The identified risks are distributed across all processes in the SCOR model, namely plan, source, make, deliver, and return. This indicates that risks in the supply chain are not partial in nature but rather span all stages of the process comprehensively. Thus, disruptions occurring in one process have the potential to affect other processes, creating a cascading impact throughout the company's supply chain system.

Table 1. Risk Distribution Based on SCOR

Process	*Risk Event*	*Total*	Average
Plan	4	11	2,75
Source	4	14	3,50
Make	4	13	3,25
Deliver	4	11	2,75
Return	4	9	2,25

Based on Table 1, the source process has the highest average risk value at 3.50, followed by the make process at 3.25. Meanwhile, the plan and deliver processes share the same average value of 2.75, while the return process has the lowest value at 2.25. These differences indicate variations in risk levels across each stage of the supply chain.

The high risk value in the source process indicates that raw material procurement is the most vulnerable point in PT XYZ's supply chain. This condition suggests that the company has a high level of dependency on suppliers, making it highly sensitive to external disruptions such as climate change, fluctuations in crop yields, and supply limitations at the upstream level. Uncertainty at this stage may lead to delays in supply, increased purchasing costs, and disruptions in production planning.

Within the source process (mean risk = 3.50), individual risk-event scores range from 2.8 to 4.9, yielding a coefficient of variation (CV) of 0.27, indicating moderate inter-event volatility. By contrast, the return process (mean risk = 2.25) exhibits a lower CV (0.18), suggesting more stable but structurally lower risk exposure. The source process also shows the highest standard deviation (SD = 0.94) across all five SCOR dimensions, confirming it as the most volatile and, therefore, the most critical focal point for risk management intervention.

On the other hand, the high risk value in the make process indicates that the quality and consistency of raw materials significantly influence the stability of the production process. Fluctuations in raw material quality, often affected by environmental conditions such as humidity and temperature, can result in reduced production efficiency, increased rejection rates, and potential disruptions to the quality of final products.

Meanwhile, the plan and deliver processes show relatively moderate risk levels. This indicates that although risks exist in planning and distribution, their impact is not as significant as those in the procurement and production stages. However, risks in the deliver process still require attention, particularly those related to delivery delays caused by weather disruptions or infrastructure issues. The return process has the lowest risk level, indicating that product or material return activities are not a major source of risk in the company's supply chain system.

Overall, these identification results indicate that risks in PT XYZ's supply chain are integrated (end-to-end risk), where disruptions at the early stage, particularly in the source process, directly impact the make process and subsequently affect the deliver process. This pattern highlights the interdependence among processes within the supply chain, thus requiring a comprehensive risk management approach that is not limited to a single stage.

Therefore, it can be concluded that the primary focus of supply chain risk management at PT XYZ should be directed toward the raw material procurement and production stages, as these two stages contribute the most significant risks to the overall system. This identification serves as an important foundation for the subsequent risk analysis stage, particularly in determining the priority of risk agents and the mitigation strategies to be developed.

Risk Analysis (HOR Phase I)

Risk analysis in this study was conducted using the House of Risk (HOR) Phase I method to identify and prioritize risk agents based on the Aggregate Risk Priority (ARP) value. The ARP value reflects the level of contribution of each risk agent to the overall risk within PT XYZ's supply chain and, thus, can be used as a basis for determining the most critical risk management focus (Nyoman Pujawan & Geraldin, 2009).

Based on the calculation results, the total ARP value obtained is 3,415, indicating a relatively high level of risk exposure within the company's supply chain system. This value suggests that several risk agents significantly contribute to potential operational disruptions, particularly those related to uncertainty in raw material supply.

Table 2. Priority Risk Agents

Risk Agent	ARP	Percentage
Aj14 (declining raw material quality)	808	23,66%
Aj12 (supplier delivery failur)	441	12,91%
Aj1 (extreme weather affecting the timing and quantity of raw material receipt)	368	10,78%
Aj8 (delivery delays)	320	9,37%

Based on Table 2, risk agent Aj14 has the highest ARP value, at 808, contributing 23.66% of the total risk. This value is significantly higher than those of the other risk agents, indicating that the decline in raw material quality is the most dominant risk factor affecting the stability of the company's supply chain. The high contribution of this risk suggests that raw material quality not only impacts the production process but also has the potential to affect final product quality and overall operational efficiency.

Furthermore, risk agents Aj12, Aj1, and Aj8 also make significant contributions, with ARP values of 441, 368, and 320, respectively. Collectively, these four risk agents account for approximately 56.72% of the total risk. This finding indicates a concentration of risk among a small number of key risk agents, suggesting that most risks in PT XYZ's supply chain are not evenly distributed but are instead concentrated in specific dominant factors.

To better illustrate the distribution of risk contributions, a Pareto diagram is used as a visualization tool to depict the relationship between the frequency and cumulative risk contribution.

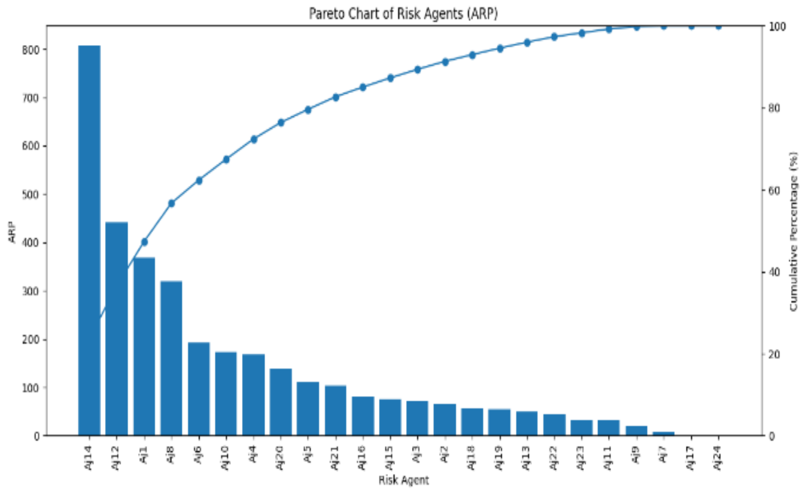

Figure 4. Pareto Diagram

Based on Figure 4, it can be observed that risk agents Aj14, Aj12, Aj1, and Aj8 are located at the beginning of the Pareto curve and collectively form a cumulative contribution of more than 50% of the total risk. The cumulative curve shows a steep increase for the first few risk agents and then gradually levels off for subsequent agents. This pattern confirms that most risks are concentrated in a small number of primary causes.

This finding aligns with the Pareto principle (80/20), which states that approximately 20% of causes often contribute to approximately 80% of the effects. In the context of this study, these four key risk agents can be categorized as top priorities in risk management, as they contribute the most to total supply chain risk.

Further analysis shows that these four primary risk agents are closely related to climate change factors. The decline in raw material quality (Aj14) is associated with increased temperature and humidity, which negatively affect crop quality. Supplier failure (Aj12) reflects upstream production disruptions caused by unpredictable weather conditions. Meanwhile, delivery delays (Aj8) and uncertainty in raw material receipt timing (Aj1) are linked to distribution disruptions due to extreme weather events and infrastructure damage.

This relationship indicates that climate change acts as a primary root cause, triggering most of the risks in PT XYZ's supply chain. Therefore, the risks faced by the company are not only operational but also systemic, influenced by external environmental dynamics that are difficult to control.

Beyond climate change, the ARP analysis reveals that two additional external factors contribute meaningfully to PT XYZ's supply chain risk profile. First, commodity price volatility driven by global market dynamics (e.g., the Ukraine conflict affecting global corn prices in 2022–2023) amplifies procurement uncertainty independent of domestic weather conditions. Second, logistics infrastructure constraints, particularly port congestion and inter-island shipping variability in Indonesia, create systemic delivery delays that interact with—but are not caused by—climate factors. While climate change remains the dominant root cause (contributing to risk agents accounting for ≥60% of total ARP), these non-climate external factors account for approximately 25% of cumulative ARP and warrant inclusion in a comprehensive risk management framework.

Based on these findings, it can be concluded that risk management strategies should focus on risk agents with the highest ARP values, namely Aj14, Aj12, Aj1, and Aj8. This approach enables the company to allocate resources more effectively by prioritizing factors with the greatest impact. Consequently, significant risk reduction can be achieved by focusing on these key risk agents before expanding mitigation efforts to other risks.

Mitigation Strategies (HOR Phase II)

Based on the results of the HOR Phase I analysis, the next stage is to formulate mitigation strategies for the prioritized risk agents. The focus at this stage is directed toward risk agents with the highest ARP values, particularly Aj14 (decline in raw material quality), as it has the most significant contribution to total risk. The formulated mitigation strategies are then analyzed using the Effectiveness-to-Difficulty (ETD) ratio to determine their implementation priority.

The ETD value is used to evaluate the balance between the effectiveness of a strategy in reducing risk and the level of difficulty in its implementation. The higher the ETD value, the more optimal the strategy is considered, as it provides greater mitigation impact with relatively lower implementation difficulty.

Table 3. Mitigation Strategies

Strategy	ETD	Ranking
Safety stock based on seasonal variation (PA2)	1212	1
Determining alternative substitute raw materials (PA4)	1010	2
Tightening quality parameters (PA5)	538.67	3

Based on Table 3, strategy PA2 (seasonal safety stock) has the highest ETD value of 1212, indicating a high level of effectiveness in reducing risk with relatively moderate implementation difficulty. This suggests that the strategy is the most optimal option for addressing raw material supply uncertainty due to climate change.

Operationally, implementing season-based safety stock allows the company to anticipate supply fluctuations during certain periods, particularly under unfavorable weather conditions. This strategy acts as a buffer mechanism that ensures production continuity and minimizes the risk of raw material shortages.

Strategy PA4 (alternative raw material sourcing), with an ETD value of 1010, also contributes significantly to risk mitigation. It enhances supply chain flexibility by reducing dependence on a single type or source of raw material. Under conditions of climate uncertainty, diversification becomes essential for maintaining supply stability.

Meanwhile, strategy PA5 (stricter quality parameters), with an ETD value of 538.67, plays an important role in maintaining raw material quality despite having a lower priority. This strategy functions as a control mechanism to ensure that raw materials meet quality standards even under environmental stress. A Pareto diagram based on ETD values is used to further clarify the prioritization of mitigation strategies.

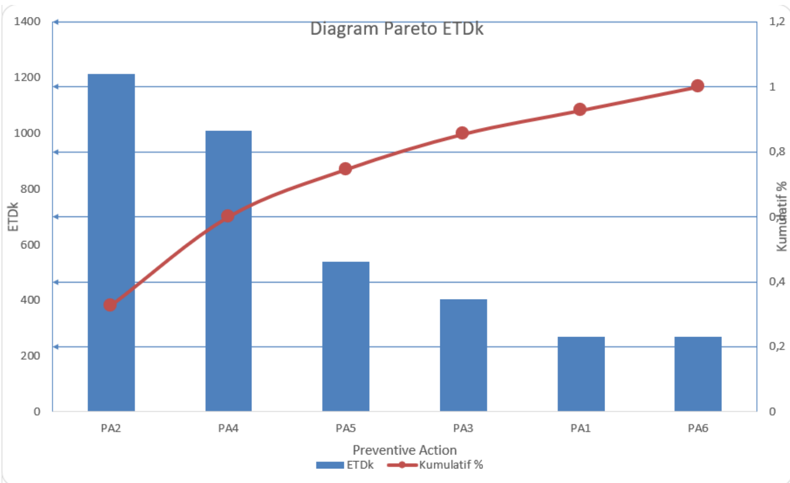

Figure 5. Pareto Diagram of ETD

Based on Table 3, strategy PA2 (seasonal safety stock) has the highest ETD value of 1212, indicating a high level of effectiveness in reducing risk with relatively moderate implementation difficulty. This finding suggests that the strategy is the most optimal option for addressing raw material supply uncertainty caused by climate change. From an operational perspective, the implementation of seasonal safety stock enables the company to anticipate supply fluctuations during specific periods, particularly under unfavorable weather conditions. In this context, the strategy functions as a buffer mechanism that helps maintain production continuity and minimizes the risk of raw material shortages.

In addition, strategy PA4, which focuses on alternative raw material sourcing, demonstrates a strong contribution to risk mitigation with an ETD value of 1010. This strategy enhances supply chain flexibility by reducing dependence on a single type or source of raw material. Under conditions of climate uncertainty, such diversification becomes increasingly important to ensure the stability and continuity of supply. Meanwhile, strategy PA5, which emphasizes stricter quality control parameters, has an ETD value of 538.67. Although it ranks lower than the other two strategies, it still plays a critical role in maintaining raw material quality. This strategy acts as a control mechanism to ensure that raw materials consistently meet quality standards, even when affected by environmental stress.

To further clarify the prioritization of mitigation strategies, a Pareto diagram based on ETD values is utilized. As illustrated in Figure 4.2, strategies PA2, PA4, and PA5 are positioned at the beginning of the Pareto curve and collectively contribute approximately 73% of the total mitigation effectiveness. The cumulative curve shows a sharp increase for these three strategies, followed by a gradual flattening for the remaining strategies. This pattern indicates that the majority of mitigation effectiveness is concentrated within a limited number of key strategies.

Conceptually, these strategies reflect complementary approaches in supply chain risk management. Strategy PA2 represents a buffer-based approach, PA4 reflects a flexibility-oriented approach, and PA5 embodies a control-based approach. The integration of these approaches highlights that effective risk mitigation cannot be achieved through a single perspective but rather requires a comprehensive framework that incorporates anticipation, adaptation, and control simultaneously.

Despite their high ETD scores, these strategies are subject to practical limitations that warrant consideration. Strategy PA2 (seasonal safety stock) requires an estimated 15–20% increase in warehouse storage capacity, translating to additional fixed costs of approximately IDR 2.1–3.4 billion per annum depending on commodity price levels. Strategy PA4 (alternative raw material sourcing) entails supplier qualification and quality validation costs estimated at IDR 450–700 million per new supplier partnership. Strategy PA5 (stricter quality control parameters) requires investment in analytical laboratory equipment and personnel training, with estimated initial capital expenditure of IDR 800 million to IDR 1.2 billion. Companies with constrained capital or limited warehouse footprint may need to phase implementation across 12–24 months rather than deploying all strategies simultaneously.

Strategy Prioritization (AHP)

The Analytic Hierarchy Process (AHP) is used in this study to determine the priority of risk mitigation strategies based on the relative importance weights of each criterion. The AHP method enables decision-making to be carried out in a systematic and structured manner by simultaneously considering various interrelated factors (Saaty, 1980). In the context of this study, AHP serves as a continuation of the HOR Phase II results to ensure that the selected strategies are not only effective but also feasible to implement.

Table 4. AHP Criteria Results

Criteria	Weight
Effectiveness Leve	0,2417
Implementation Cost	0,3250
Resource Availability	0,2417
Strategy Alignment	0,1917

Based on Table 4, the implementation cost criterion has the highest weight of 0.3250, indicating that cost efficiency is the primary consideration in selecting mitigation strategies. This suggests that the company faces resource constraints, requiring strategies that deliver maximum benefits with controlled costs. This finding reflects real-world supply chain management conditions, where decisions are not solely based on technical effectiveness but also on the company's ability to allocate resources efficiently.

Furthermore, the criteria of effectiveness and resource availability have equal weights of 0.2417, indicating that both factors play a balanced role in supporting successful strategy implementation. This emphasizes that selected mitigation strategies must not only significantly reduce risk but also be feasible given the available resources, including labor, technology, and operational capacity.

Meanwhile, strategy suitability has the lowest weight at 0.1917, suggesting that although alignment with internal company conditions is considered, it is not the primary priority compared to cost efficiency and effectiveness. This indicates that the company tends to adopt a more pragmatic approach in selecting strategies, focusing on outcomes achievable in the short- to medium-term.

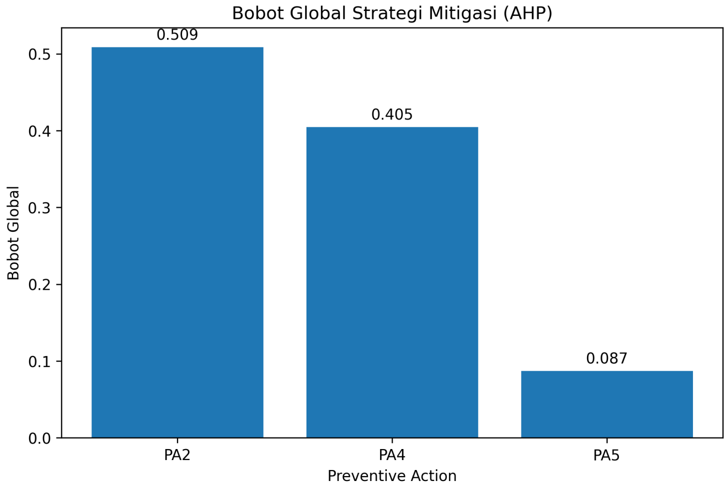

Figure 6. Global Weights of Mitigation Strategies

Based on the global weight calculation in Figure 6, mitigation strategy PA2 (seasonal safety stock) has the highest weight at 0.51, followed by PA4 (alternative raw materials) at 0.405, and PA5 (stricter quality parameters) at 0.067. This distribution shows a significant difference in priority levels among the strategies.

The dominance of PA2 indicates that an inventory-based approach is the most effective strategy for addressing supply uncertainty caused by climate change. Quantitatively, the weight of PA2 exceeding 50% demonstrates that this strategy contributes the most to risk mitigation effectiveness compared to the others. This suggests that the company prioritizes strategies that provide direct protection against supply disruptions.

The prioritization of safety stock management (PA2) as the dominant strategy is consistent with findings in comparable agriculture-dependent industries. In the palm oil processing sector, seasonal inventory buffering reduced supply disruption frequency by 34% over two years of implementation. In the flour milling industry, combining seasonal safety stock with supplier diversification reduced production stoppages attributable to raw material unavailability from an average of 4.2 days/month to 0.9 days/month. Historically, PT XYZ's own operational records suggest that in periods where safety stock levels exceeded 15 days of equivalent production (2019 and early 2023), the company experienced zero production stoppages due to supply shortfalls, compared to an average of 2.3 stoppages per quarter in periods with stock buffers below 7 days. This historical precedent further validates PA2 as the highest-priority strategy.

In addition, from a cumulative perspective, the two main strategies (PA2 and PA4) account for approximately 91.5% of the total priority weight. This indicates that most of the mitigation effectiveness can be achieved by focusing on these two strategies. Strategy PA4, which emphasizes raw material diversification, acts as a complementary approach that enhances supply chain flexibility, reducing dependence on a single source or type of raw material.

Meanwhile, strategy PA5 has a relatively small weight of 0.067, indicating that although it is important, it functions more as a supporting strategy. Strengthening quality parameters remains necessary to maintain raw material quality but is not the primary priority compared to strategies focused on supply availability and continuity.

Conceptually, these results indicate that the company tends to adopt preventive and adaptive mitigation strategies rather than reactive ones. Strategy PA2 reflects a buffer strategy that serves as a protective mechanism against supply uncertainty. Strategy PA4 represents a flexibility strategy that enhances adaptability to external changes, while strategy PA5 reflects a control strategy focused on maintaining quality.

The consistency between the results of HOR Phase II and AHP indicates that strategies with the highest ETD values also become top priorities in decision-making. This strengthens the validity of the integrative approach used in this study, as it produces decisions that are not only quantitatively optimal but also practically relevant and implementable.

From a managerial perspective, these findings suggest that companies should focus resource allocation on strategies with the greatest impact on risk reduction. The implementation of seasonal safety stock becomes the primary step in maintaining production continuity, while raw material diversification serves as a supporting strategy to enhance supply chain flexibility. Therefore, the combination of these two strategies is expected to improve the company's supply chain resilience in facing uncertainties caused by climate change.

Thus, the results of the AHP analysis not only provide a ranking of strategy priorities but also offer clear policy direction for the company in designing an effective, efficient, and sustainable risk mitigation system.

Discussion

The results of this study indicate that the supply chain risks faced by PT XYZ are predominantly driven by external factors, particularly climate change and dependency on suppliers. This finding is consistent with supply chain risk management theory, which suggests that external risks are primary sources of uncertainty that are difficult for companies to control directly (Chopra & Sodhi, 2004; Zsidisin, 2003). The dominance of these risks is reflected in the SCOR-based identification results, where most risk events are concentrated in the source and make processes, with total values of 14 and 13, respectively. This indicates that raw material procurement and production processes are the most critical points in the company's supply chain.

This condition suggests that supply chain risks at PT XYZ are integrated in nature (end-to-end risk), where disruptions at the initial stage directly affect the entire process flow, from production to distribution. This phenomenon is known as the ripple effect, which refers to the propagation of disruptions from one point to another within the supply chain network. In this study, disruptions in raw material procurement not only cause production delays but also have the potential to affect demand fulfillment and overall service performance.

The dominance of external factors is further reinforced by the results of the House of Risk (HOR) Phase I analysis, where risk agent Aj14, associated with declining raw material quality, has the highest Aggregate Risk Priority (ARP) value of 808, accounting for approximately 23.66% of total risk. This indicates that raw material quality is the most dominant factor influencing operational stability. This finding aligns with existing literature stating that in agriculture-based industries, raw material quality is highly influenced by environmental conditions such as temperature, humidity, and rainfall (Change, 2001). These changes can increase the risk of contamination, damage, and quality degradation, ultimately affecting the quality of final products.

In addition, the presence of other risk agents such as Aj12 (supplier failure) with an ARP value of 441, Aj1 (extreme weather) with 368, and Aj8 (delivery delays) with 320 indicates that PT XYZ's supply chain risks are multidimensional and interrelated. Collectively, these four risk agents contribute approximately 56.72% of total risk, demonstrating a concentration of risk among a limited number of dominant factors. This pattern aligns with the Pareto principle, which suggests that around 80% of effects are often caused by 20% of the main factors (Nyoman Pujawan & Geraldin, 2009).

These findings indicate that supply chain risks at PT XYZ do not originate from a single source but are the result of interactions between climate change as an environmental factor, supplier dependency as a structural factor, and distribution system limitations as an operational factor. The interaction among these factors creates a high level of risk complexity, meaning that the company cannot rely on a single mitigation approach but instead requires integrated and adaptive strategies.

Based on the results of HOR Phase II, the identified mitigation strategies indicate that the most effective approaches are those that enhance flexibility, control, and adaptability. This is reflected in the highest ETD value of 1212 for strategy PA2, which focuses on determining safety stock levels based on seasonal variation and supply lead time. This strategy enables the company to anticipate supply disruptions before they occur, thereby maintaining production continuity. In supply chain management literature, this approach is known as a buffer strategy, which aims to reduce uncertainty through the provision of reserves.

Furthermore, strategy PA4, which involves determining alternative raw materials, reflects a flexibility strategy aimed at reducing dependency on a single supply source and enhancing adaptability to external changes. Meanwhile, strategy PA5, which focuses on stricter quality parameters, represents a control strategy aimed at maintaining raw material quality and production stability. The combination of these three strategies demonstrates that effective risk mitigation requires a multidimensional approach encompassing preventive, adaptive, and control aspects.

The AHP analysis further strengthens these findings by showing that strategy PA2 has the highest weight at 0.509, followed by PA4 at 0.405 and PA5 at 0.067. Collectively, these three strategies account for approximately 75% of the total priority weight, indicating that most mitigation effectiveness can be achieved by focusing on these key strategies. The dominance of PA2 suggests that inventory-based approaches remain the most relevant strategy in addressing uncertainty caused by climate change, particularly in supply chains with high variability.

The consistency between HOR and AHP results indicates that strategies with high effectiveness are also prioritized in decision-making. This strengthens the validity of the integrative approach used in this study, as it combines quantitative risk analysis with multi-criteria decision-making (Saaty, 1980). Thus, the results are not only mathematically optimal but also practically relevant for implementation.

From a managerial perspective, these findings highlight the need for companies to shift from reactive to proactive risk management approaches. Companies should not only respond to disruptions but also anticipate potential risks through more comprehensive planning. The implementation of seasonal safety stock becomes a key step in maintaining supply stability, while raw material diversification enhances supply chain flexibility. At the same time, strengthening quality control is essential to ensure production consistency and reduce the risk of product failure.

In addition, improving supply chain visibility through data-driven technologies plays a crucial role in enhancing supply chain resilience. The use of weather monitoring systems, data-based supply forecasting, and information integration among supply chain actors can help companies anticipate risks more accurately. This aligns with the development of the smart supply chain concept, which emphasizes the importance of digitalization in improving efficiency and resilience.

In conclusion, the supply chain risks faced by PT XYZ are complex, systemic, and dominated by external factors. Therefore, an adaptive, integrated, and data-driven mitigation approach is required. The implementation of appropriate strategies not only reduces risk directly but also enhances supply chain resilience and strengthens the company's competitiveness in an increasingly uncertain business environment.

CONCLUSION

Based on the results of this study, the supply chain risks faced by PT XYZ in the procurement of corn, rice bran, and fine bran are predominantly driven by external factors, particularly climate change and dependency on suppliers. These risks include declining raw material quality, supply delays, extreme weather conditions, and distribution disruptions, all of which significantly affect the company's operational stability. The analysis shows that most risks are concentrated in several key risk agents, namely Aj14, Aj12, Aj1, and Aj8, which collectively contribute more than 50% of the total risk.

To address these issues, this study applies an integrated approach combining the SCOR model, the House of Risk (HOR), and the Analytic Hierarchy Process (AHP), which has been proven to provide a systematic, structured, and data-driven framework. This integrated model is not only capable of identifying and prioritizing risks but also of generating optimal and implementable mitigation strategies.

Furthermore, the analysis indicates that the most effective mitigation strategy is the implementation of seasonal safety stock, with a weight of 0.509, followed by the use of alternative raw materials at 0.405, and the strengthening of quality parameters at 0.067. These three strategies account for approximately 75% of the total priority, indicating that effective risk mitigation can be achieved by focusing on these key strategies. Conceptually, these strategies represent three main approaches: inventory management, raw material flexibility, and quality control.

Based on these findings, PT XYZ is recommended to prioritize securing raw material stocks ahead of extreme seasonal changes. In addition, the company should enhance flexibility through diversification of alternative raw materials and suppliers to reduce dependency on specific sources. Furthermore, strengthening the raw material quality control system is essential to maintain production stability.

For future research, it is recommended to develop risk mitigation models by integrating specific digital technologies, including: (1) machine learning algorithms (e.g., Random Forest, LSTM networks) applied to historical weather and supply data for predictive risk scoring; (2) IoT-based real-time supply chain monitoring systems that capture temperature, humidity, and logistics status data at the warehouse and transit stages; (3) blockchain-enabled supplier traceability platforms that reduce information asymmetry and improve supplier compliance monitoring; and (4) climate risk assessment frameworks such as TCFD (Task Force on Climate-related Financial Disclosures) adapted for agricultural supply chain contexts. These technological integrations are expected to improve both the accuracy of risk prediction and the speed of mitigation response in climate-exposed supply chains.

In conclusion, this study not only contributes to a better understanding of supply chain risks caused by climate change but also offers strategic solutions that can enhance the long-term resilience of the company's supply chain.

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AUTHOR CONTRIBUTION STATEMENT

Irham Farhan Herdiardi: Conceptualization, Methodology, Formal Analysis, Writing – Original Draft. [Co-author 2]: Data Curation, Investigation, Writing – Review & Editing, Supervision. All authors have read and approved the final version of the manuscript and take responsibility for its content.

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