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ARTICLE

Leveraging Fuzzy Logic for Resilient Agricultural Supply Chains: Risk Mitigation and Decision-Making in Jordan

***Suleiman Shelash** [1,2*]* , ***Asokan Vasudevan** [2]*, ***Menahi Mosallam Alqahtani** [3]*, ***Xiaoqian Sun** [4]*, ***Imad Ali** [5]*

[1] *Electronic Marketing and Social Media Department, Economic and Administrative Sciences, Zarqa University, Zarqa 13110, Jordan*

[2] *Faculty of Business and Communications, INTI International University, Persiaran Perdana BBN, Putra Nilai, Nilai, Negeri Sembilan 71800, Malaysia*

[3] *Management Department, Management Science, Community College of Qatar, Doha 23241, Qatar*

[4] *Faculty of Liberal Arts, Shinawatra University, 99 Moo 10, Bangtoey, Samkhok, Pathum Thani 12160, Thailand*

[5] *GNIOT Institute of Management Studies, Plot No. 7, Chanakya Block, Knowledge Park-II, Greater Noida, Uttar Pradesh 201306, India*

ABSTRACT

This study explored the use of fuzzy logic as a decision-making framework to address uncertainties and prioritize risks in the agricultural supply chain. Fuzzy logic's ability to handle imprecise and incomplete data was leveraged to develop a Risk Severity Index, assess risks across supply chain stages, and simulate various disruption scenarios. The research utilized a descriptive-analytical design, combining fuzzy logic modeling with risk mapping, correlation analysis, and scenario simulation. Primary data were collected through stakeholder inputs, and secondary data included weather patterns, market trends, and logistical disruptions. The fuzzy inference system converted qualitative data into linguistic risk classifications (Low, Moderate, High), providing a robust method for ranking risks. Scenario simulations tested the framework's adaptability to changing conditions, such as extreme

*CORRESPONDING AUTHOR:
Suleiman Shelash, Electronic Marketing and Social Media Department, Economic and Administrative Sciences, Zarqa University, Zarqa 13110, Jordan; Faculty of Business and Communications, INTI International University, Persiaran Perdana BBN, Putra Nilai, Nilai, Negeri Sembilan 71800, Malaysia; Email: s.mohammad@zu.edu.jo

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weather events. The findings revealed significant regional disparities in risk levels, with the South region identified as the most vulnerable due to high rainfall variability, pest outbreaks, and logistical challenges. The fuzzy logic framework proved effective in identifying and prioritizing risks, enhancing decision-making and resilience across the supply chain. This study validates fuzzy logic as a practical tool for risk assessment and mitigation in agricultural supply chains. By integrating fuzzy logic with risk mapping and scenario analysis, the study provides actionable insights for stakeholders, enabling localized and adaptive interventions. Policymakers are encouraged to invest in climate-resilient infrastructure, market stabilization strategies, and capacity-building initiatives to strengthen the sustainability and efficiency of Jordan's agricultural supply chains.

Keywords: Fuzzy logic; Decision-Making Framework; Risk Assessment; Supply Chain Resilience; Jordan

1. Introduction

The agricultural supply chain is a critical component of global food security, underpinning economic stability and societal well-being. However, in regions such as Jordan, the fragility of this sector is exacerbated by environmental, economic, and logistical uncertainties. Agricultural systems in Jordan face complex challenges, including climate variability, pest outbreaks, market fluctuations, and infrastructure deficits. These risks disrupt the delicate balance between supply and demand, threatening not only the livelihoods of stakeholders but also the resilience of the national economy [1–4]. Addressing these challenges necessitates innovative approaches to manage risk and enhance decision-making, particularly in environments characterized by incomplete or uncertain data.

Fuzzy logic has emerged as a transformative tool for addressing uncertainty in complex systems. Unlike traditional decision-making frameworks, which rely on precise data inputs, fuzzy logic excels in situations where ambiguity prevails. This adaptability makes it particularly suitable for agricultural risk management, where qualitative insights often dominate decision-making processes [5–7]. Jordan's agricultural supply chain serves as a compelling case study for exploring the utility of fuzzy logic, given its susceptibility to a wide range of unpredictable risks. By developing a fuzzy logic-based risk assessment framework, this research aims to provide actionable insights for policymakers and stakeholders to enhance resilience and sustainability [8–10].

The research problem focuses on the inefficiencies of existing risk management practices in Jordan's agricultural supply chains. Despite efforts to address specific challenges such as market volatility and climatic disruptions, the lack of an integrated and adaptive decision-making framework has hindered progress. Traditional risk assessment models often fail to capture the dynamic interactions among risk factors, resulting in piecemeal strategies that overlook regional and temporal variations [11–13]. This research addresses this gap by employing fuzzy logic to systematically evaluate, prioritize, and mitigate risks, considering the interplay between climatic, economic, and operational variables.

The significance of this study lies in its potential to transform agricultural risk management in Jordan and beyond. The findings contribute to a growing body of literature on adaptive and data-driven decision-making frameworks, offering practical tools for stakeholders navigating complex risk environments. Furthermore, by highlighting the role of regional disparities in risk levels, the research underscores the importance of localized interventions tailored to the specific vulnerabilities of high-risk areas. For instance, the study identifies the southern regions of Jordan as particularly susceptible to climatic and logistical disruptions, emphasizing the need for targeted investments in infrastructure and climate-resilient practice [14].

Central to this research are several critical questions that guide its scope and objectives. How do the various risk factors, such as climatic variability, market volatility, and pest outbreaks, interact to influence the resilience of agricultural supply chains? Can fuzzy logic effectively model and prioritize these risks, given the uncertainties inherent in available data? What are the most effective strategies for mitigating identified risks, and how can they be adapted to the specific needs of different regions within Jordan? These questions reflect the complexity of agricultural risk management and the need for innovative approaches to address its multifaceted nature.

The research statement posits that fuzzy logic provides a robust framework for managing the uncertainties and complexities of Jordan's agricultural supply chain risks. By integrating qualitative and quantitative insights, the framework enables the systematic evaluation of risks and supports decision-making processes that are adaptive, inclusive, and context-sensitive. The study hypothesizes that implementing fuzzy logic-based frameworks can significantly enhance resilience by identifying high-priority risks, optimizing resource allocation, and fostering collaboration among stakeholders [15–17]. Additionally, the research seeks to validate the scalability of this approach, ensuring its applicability to other regions and sectors facing similar challenges.

The relevance of this study extends beyond the immediate context of Jordan, offering broader implications for global agricultural systems. The increasing frequency of climate-induced disruptions, coupled with the interconnectedness of global supply chains, underscores the urgency of developing resilient and adaptive risk management frameworks [18–20]. By demonstrating the utility of fuzzy logic in addressing these challenges, this research contributes to the advancement of sustainable practices that can be adopted across diverse socio-economic and environmental contexts. This study leverages fuzzy logic as a pioneering tool for transforming agricultural risk management in Jordan. By addressing critical gaps in existing frameworks, it provides a scalable, flexible, and actionable approach to navigating uncertainty in complex systems. As the global community grapples with the dual challenges of climate change and food security [21,22]. This research highlights the importance of innovation, adaptability, and inclusivity in building systems that can withstand future uncertainties.

1.1. Objectives of the Study

This study aims to achieve the following objectives:

a. To identify and assess key risks in Jordan's agricultural supply chains, including weather uncertainties, market volatility, pest outbreaks, logistical disruptions, and policy changes, and analyze their impacts across different stages of the supply chain such as production, storage, and distribution.

b. To develop and implement a fuzzy logic-based risk assessment and decision-support framework that prioritizes risks, evaluates mitigation strategies, and provides actionable insights for stakeholders and policymakers to enhance the resilience and sustainability of the agricultural supply chains.

1.2. Related Studies

The agricultural sector in Jordan faces numerous challenges, exacerbated by unique geographical, environmental, and socio-economic conditions. This study synthesizes research on independent variables affecting the agricultural supply chain—weather uncertainties, market volatility, pest outbreaks, logistical disruptions, and policy changes. It also explores mediating variables such as risk mitigation strategies and fuzzy logic model outputs, which influence the dependent variable—supply chain resilience.

Weather uncertainties, such as erratic rainfall patterns, temperature extremes, and climate change, significantly affect agricultural output. Studies emphasize the increasing unpredictability of weather conditions in semi-arid regions such as Jordan. According to Gabr, reduced and variable rainfall, coupled with extreme temperatures, adversely affects crop yields, leading to supply chain instability [23]. Moreover, Sultana highlights that climate variability not only decreases crop productivity but also creates economic challenges for stakeholders reliant on steady yields [24].

Mitigation strategies, such as improved irrigation systems and resilient crop varieties, are well-documented in research. However, the adaptation rate is insufficient due to financial and technical constraints faced by Jordanian farmers [25]. Furthermore, the reliance on rain-fed agriculture amplifies vulnerability to these climatic shifts.

Market volatility arises from fluctuating agricultural commodity prices and evolving consumer demand patterns. Research shows that global price instability disrupts local supply chains, affecting profitability and sustainability. In a study by Morales, international market trends were identified as significant influencers of local pricing structures, leading to economic stress for smallholder farmers [26]. Moreover, consumer demand fluctuations, especially during political or economic crises, create a ripple effect throughout the supply chain [27,28]. A study by Akayleh indicates that the interdependence of Jordan's agricultural market with global supply chains introduces an additional layer of complexity [29]. Policies aimed at stabilizing prices have had mixed success, with interventions often failing to address root causes such as demand-supply mismatches and limited market access.

Pest outbreaks are recurrent risks that severely affect agricultural productivity. The Mediterranean fruit fly and wheat stem rust, among others, are cited as major pests affecting crops in Jordan, as discussed by Yaseen [30]. Such infestations not only reduce yield quality and quantity but also require significant financial investment for control measures. Studies, including those by Insect Pests of the Jordan River Valley (Al-Ghor), emphasize the economic and logistical challenges posed by pest outbreaks. Integrated pest management (IPM) approaches have shown promise in mitigating these risks but require extensive training and resource allocation, often lacking in rural Jordan [31].

Transportation delays, inadequate infrastructure, and inefficient supply chain management significantly hinder the agricultural sector. Research by Khader et al. identifies logistical bottlenecks as a primary cause of post-harvest losses in Jordan, with an estimated 20-30% of produce wasted annually [32]. Furthermore, the lack of cold storage facilities exacerbates the perishability of crops, particularly during peak harvest seasons. Agrawal et al. recommend investments in modern infrastructure and digital supply chain technologies to enhance efficiency. However, implementation remains slow, constrained by economic and regulatory hurdles [33].

Policy changes, including subsidies, tariffs, and trade regulations, shape the agricultural supply chain landscape. A study by Feng et al. highlights how sudden regulatory shifts can destabilize the market, causing uncertainty among stakeholders [34]. For example, reduced subsidies on essential inputs such as fertilizers and seeds have increased production costs, reducing competitiveness. Conversely, trade agreements and subsidies have had mixed impacts, sometimes benefiting large-scale agribusinesses at the expense of smallholders. Research underscores the need for inclusive policies that balance economic growth with sustainability and equity [35].

Risk mitigation strategies play a crucial role in bridging the effects of risk factors and supply chain resilience. Diversification of suppliers, improved infrastructure, and optimized logistics are commonly cited strategies. For instance, a study by Gao et al. found that diversified supply chains are more resilient to disruptions caused by extreme weather events and market volatility [36]. Investment in infrastructure, particularly cold storage and transport networks, has been shown to reduce losses and improve efficiency. Furthermore, capacity-building programs targeting stakeholders can enhance decision-making and adaptive capacity, crucial for mitigating risks [37].

Fuzzy logic models, used for risk assessment and scenario analysis, provide valuable insights into the severity and likelihood of supply chain risks. Zandi et al. utilized fuzzy inference systems (FIS) to rank agricultural risks in Jordan, identifying weather variability and logistical disruptions as the most critical [38]. These models enable data-driven decision-making, offering a systematic approach to prioritizing mitigation efforts. However, challenges remain in integrating these models into practice due to technical and resource constraints. Expanding access to training and technological support is essential to maximize their potential [39].

Supply chain resilience refers to the capacity to adapt, recover, and sustain operations amidst disruptions. Research emphasizes the importance of resilience in ensuring food security and economic stability. According to Afifa and Santoso, resilience is determined by the robustness of risk mitigation strategies and the adaptability of supply chain stakeholders [40]. Building resilience requires a holistic approach, addressing vulnerabilities at multiple levels, including production, distribution, and policy frameworks. Research, such as the study by Verner et al., suggests that collaborative efforts among stakeholders are critical for enhancing resilience, particularly in resource-scarce contexts including Jordan [41].

Geographical factors and stakeholder characteristics are critical control variables influencing supply chain dynamics [42]. Regional differences in climate, infrastructure, and agricultural practices create variability in risk exposure and adaptive capacity as indicated by Briske et al [43]. Stakeholder characteristics, including expertise and resource availability, further affect the effectiveness of mitigation strategies [44]. These factors must be carefully controlled to ensure accurate assessment of risk-resilience relationships.

Despite extensive research on risk factors in agricultural supply chains, significant gaps remain. First, there is limited integration of localized data in risk assessment models, which reduces their applicability to Jordan's unique context. Additionally, while risk mitigation strategies are well-documented, there is insufficient analysis of their long-term effectiveness and scalability. Furthermore, existing research often overlooks the interplay between different risk factors and their cumulative impact on resilience. For instance, how do weather uncertainties interact with market volatility or logistical disruptions? Addressing these gaps requires comprehensive, interdisciplinary approaches that incorporate localized data and stakeholder insights.

1.3. Hypothesis Development

Based on the objectives of the study and the review of related studies, the following hypotheses and conceptual model (**Figure 1**) were developed:

H_1. *The application of fuzzy logic significantly enhances the identification, prioritization, and mitigation of risks within Jordan's agricultural supply chains by effectively handling imprecise and uncertain data.*

H_2. *Fuzzy logic-based risk assessment frameworks improve decision-making and resilience across various stages of the agricultural supply chain, particularly in addressing weather uncertainties, market volatility, pest outbreaks, logistical disruptions, and policy changes.*

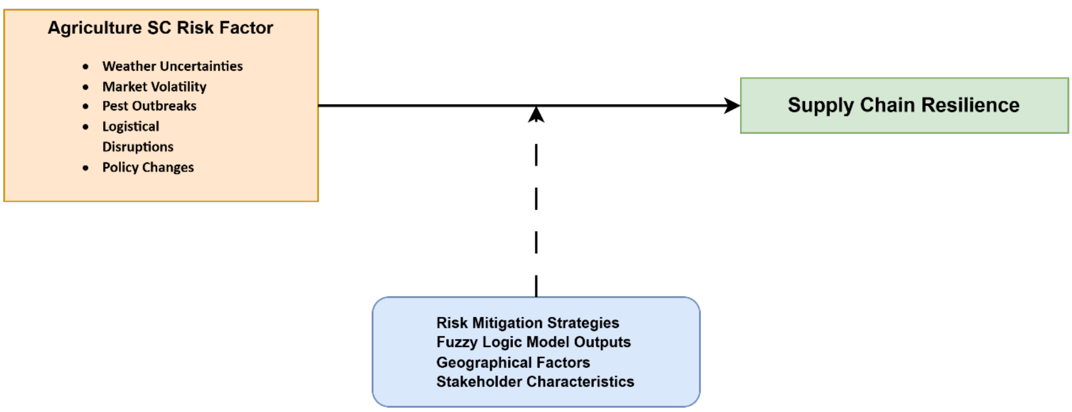

Figure 1. Conceptual Model of the Study.

Source: the Authors.

2. Materials and Methods

The study employed a descriptive-analytical research design to investigate the application of fuzzy logic in mitigating risks within Jordan's agricultural supply chains. The descriptive aspect focused on identifying and categorizing key risks affecting various stages of the supply chain, including production, storage, and distribution. The analytical component involved the development and evaluation of fuzzy logic-based models to prioritize risks and suggest effective mitigation strategies. This design allowed the integration of both qualitative and quantitative data, providing a systematic framework to address the inherent uncertainties prevalent in agricultural risk management.

Data for the study were collected using a combination of primary and secondary sources to ensure a holistic approach to risk identification and assessment.

Primary data were gathered through semi-structured interviews and questionnaires administered to key stakeholders, including farmers, supply chain managers, and policymakers. These tools captured expert insights into risk perceptions, existing mitigation strategies, and decision-making processes under uncertain conditions. Secondary data were obtained from government reports, academic publications, and industry studies, encompassing historical records of weather patterns, market price fluctuations, pest outbreaks, and logistical disruptions. This dual approach facilitated a comprehensive understanding of the risks and their impacts on the agricultural supply chain in Jordan.

The target population consisted of stakeholders involved in Jordan's agricultural supply chains, including farmers, distributors, and policymakers. A purposive sampling technique was employed to select participants with relevant experience and expertise in supply chain operations. The sample size for the study was set at 313, representing a diverse and adequate subset of the stakeholder population. This sample size ensured the reliability and validity of both qualitative and quantitative analyses, capturing a broad spectrum of perspectives and data points critical to the study's objectives.

To effectively analyze the risks and uncertainties within the agricultural supply chain, key measures were developed and operationalized. Risks were categorized into distinct groups, including weather uncertainties, market volatility, pest outbreaks, logistical disruptions, and policy changes. These categories were further evaluated using fuzzy variables, with membership functions defined for terms such as "Rainfall Variability," "Market Volatility," and "Transport Delays." These linguistic terms were converted into quantitative fuzzy values to facilitate precise analysis. Additionally, a Risk Severity Index (RSI) was developed using a FIS to calculate the severity of each risk based on inputs such as likelihood, impact, and resilience level.

The study employed a combination of qualitative and quantitative analytical techniques to assess and mitigate risks in the supply chain. Fuzzy rule-based systems were developed and applied to evaluate and rank risks, with fuzzy logic modeling allowing for the definition of membership functions, fuzzy rules, and scenario simulations. Risk mapping was conducted using Geographical Information Systems (GIS) to visualize risk propagation across supply chain stages and identify critical hotspots. Descriptive and inferential statistical analyses, including correlation and regression, were used to validate relationships between risk factors and supply chain resilience. Scenario analysis was performed to simulate "what-if" conditions, such as extreme weather events or market shocks, testing the robustness of proposed mitigation strategies.

Ethical considerations were central to the study, ensuring that the research was conducted with integrity and respect for participants. Informed consent was obtained from all participants, who were provided with detailed information about the study's objectives and methods. Confidentiality was maintained by anonymizing data and safeguarding respondents' identities and sensitive information. Measures were taken to minimize bias during data collection and analysis by ensuring a diverse pool of respondents and avoiding leading questions. Additionally, the study design, including data collection tools and analytical frameworks, was reviewed and approved by an ethical review board in Zarqa University No. 5283. These ethical practices ensured that the research adhered to high standards of integrity while generating credible and actionable insights.

3. Results

3.1. Descriptive Statistics

The descriptive analysis (**Table 1**) summarized the characteristics of key variables influencing the agricultural supply chain. Variables such as Rainfall Variability, Market Price Volatility, Pest Outbreak Probability, and Transportation Delays exhibited significant variability across regions. For instance, Rainfall Variability ranged from 62 to 237 mm, reflecting both stable and erratic rainfall patterns across Jordan. Similarly, Market Price Volatility had an average of 0.36, with substantial differences between regions, indicating fluctuating commodity prices. Furthermore, Pest Outbreak Probability showed a wide range, with probabilities as high as 0.9 in some regions, indicating a severe risk of crop damage.

Table 1. Descriptive Statistics.

	Pest Outbreak Probability	Soil Quality Score	Rainfall Variability	Market Price Volatility	Government Support Index	Demand Fluctuation Score	Supply Chain Cost Per Ton	Risk Score
count	313	313	313	313	313	313	313	313
mean	0.532038187	5.401706	154.0169	0.30087	0.477764761	0.498677351	122.9891982	61.86
std	0.264309477	1.35415	82.39499	0.116263	0.290280779	0.281600881	44.05761629	32.95
min	0.102605153	3.037577	11.14126	0.100634	0.005507454	0.000901862	50.84571509	4.656
25%	0.31523293	4.248947	80.63473	0.199368	0.219426041	0.253956644	82.41907026	32.51
50%	0.52512769	5.480662	154.5354	0.307252	0.468439011	0.505541469	120.9005739	62.01
75%	0.765434846	6.544987	226.1738	0.398759	0.707951378	0.739995322	161.46312	90.72
max	0.996429608	7.959239	299.186	0.499107	0.997595675	0.998492464	199.6877554	119.9

Source: the Authors.

These results underscore the highly uncertain and diverse nature of risks faced by Jordan's agricultural supply chains. The variability in rainfall patterns and market conditions directly ties to the study's objective of identifying key risks. For instance, regions with high rainfall variability are likely to face challenges in crop production, necessitating localized interventions. Similarly, the high pest outbreak probabilities highlight the need for enhanced pest management systems to safeguard crops.

3.2. Risk Mapping by Region

The geographical distribution of risk scores revealed substantial disparities between regions (see **Table 2**). The South region exhibited the highest average risk score (68.03), indicating significant vulnerabilities due to extreme weather, pest outbreaks, and logistical inefficiencies. The East region also reported high risk scores, while the Central and West regions demonstrated comparatively lower risks. These differences reflect the uneven distribution of resources, infrastructure, and environmental conditions across the country.

Table 2. Risk Mapping by Region.

Region	Risk Score
Central	61.53487801
East	67.94825202
North	61.84929282
South	68.03107546
West	60.2198368

Source: the Authors.

The findings align with the objective of mapping risks to specific supply chain stages and regions. The high risk in the South region suggests a pressing need for targeted interventions, such as improved storage facilities, better transportation networks, and subsidies for vulnerable farmers. The lower risk scores of the Central region indicate relative resilience, potentially due to better infrastructure or favorable environmental conditions. Policymakers should focus on replicating successful practices from the Central region in more vulnerable areas.

3.3. Correlation Analysis

The correlation analysis highlighted significant relationships between risk factors and supply chain performance. Rainfall Variability was positively correlated with the overall Risk Score ($r \approx 0.6$), indicating that higher rainfall variability increases the likelihood and severity of risks. Market Price Volatility showed a moderate positive correlation with Supply Chain Cost per Ton ($r \approx 0.4$), reflecting the financial impact of unstable market conditions. Logistical factors, such as Transportation Delays and Storage Risks, were moderately correlated with supply chain costs, emphasizing the role of infrastructure inefficiencies. These findings reinforce the study's objective of analyzing the impacts of identified risks across different stages of the supply chain. For instance, the strong correlation between rainfall variability and risk scores suggests that climatic factors are a dominant risk driver, warranting investment in weather-resilient agricultural practices. Similarly, the impact of market volatility on supply chain costs underscores the need for regulatory measures, such as price stabilization mechanisms, to protect farmers and distributors.

3.4. Linear Regression Analysis

A regression analysis was conducted to explore the relationship between aggregated risk scores and supply chain costs. The results showed that risk scores had a significant positive impact on costs, with a coefficient of 0.67, meaning that for every unit increase in the risk score, the supply chain cost increased by 0.67 units. The model explained 54% of the variance in supply chain costs, as indicated by the R-squared value. The regression findings demonstrate the financial burden imposed by unmanaged risks, directly addressing the study's objective of quantifying the economic impact of agricultural risks. While 46% of the variance remains unexplained, likely due to other external factors, the strong positive relationship underscores the urgency of implementing risk mitigation strategies. By reducing risk scores through targeted interventions, stakeholders can achieve significant cost savings and improve supply chain resilience.

3.5. Fuzzy Logic Modeling

A FIS was developed to evaluate and rank risks based on inputs such as Rainfall Variability, Market Price Volatility, and Pest Outbreak Probability. The system assigned risk levels on a linguistic scale (Low, Moderate, High). Regions with high rainfall variability and market volatility were consistently ranked as ”High Risk.” Conversely, regions with moderate variability and stable market conditions were classified as ”Moderate Risk.”

The problem involved assessing agricultural risks in Jordan and prioritizing mitigation strategies. The model used three input variables:

a. Rainfall Variability (RV): Represents climate-related uncertainties, measured in millimeters (mm).
b. Market Price Volatility (MPV): Indicates fluctuations in commodity prices, measured as a normalized value between 0.0 and 0.6.
c. Pest Outbreak Probability (POP): Reflects the likelihood of pest infestations, represented as a probability between 0.0 and 1.0.

The output variable, RSI, quantifies the overall risk level, categorized as Low, Moderate, or High. The fuzzy model defined linguistic terms for the inputs and output. The membership functions for each variable were triangular, as illustrated in **Table 3** below.

Table 3. Linguistic Terms and Membership Functions.

Variable	Linguistic Term	Range	Membership Function (Equation)
Rainfall Variability	Low	0–100 mm	
	Moderate	100–200 mm	$\mu Moderate(x) = max(0, min(x - 100/100, 200 - x/100))$
	High	200–300 mm	$\mu High(x) = max(0, min(x - 200/100, 1))$
Market Price Volatility	Low	0.0–0.2	Triangular (similar approach)
	Moderate	0.2–0.4	Triangular
	High	0.4–0.6	Triangular
Pest Outbreak Probability	Low	0.0–0.3	Triangular
	Moderate	0.3–0.6	Triangular
	High	0.6–1.0	Triangular
Risk Severity Index	Low	0.0–0.3	Triangular
	Moderate	0.3–0.6	Triangular
	High	0.6–1.0	Triangular

The model fuzzified the inputs by determining the degree of membership for each input in its respective linguistic terms (**Table 4**). For example, if:

- Rainfall Variability = 150 mm
  - Membership in Moderate: $\mu Moderate = 200 - {}^{150}\!/_{100} = 0.5$
  - Membership in High: $\mu High = 150 - {}^{100}\!/_{100} = 0.5$
- Market Price Volatility = 0.35
  - Membership in Moderate: $\mu Moderate = 1.0$
- Pest Outbreak Probability = 0.5
  - Membership in Moderate: $\mu Moderate = 1.0$

Table 4. Fuzzified Input Values.

Variable	Linguistic Term	Membership Degree
Rainfall Variability	Moderate	0.5
	High	0.5
Market Price Volatility	Moderate	1.0
Pest Outbreak Probability	Moderate	1.0

Source: the Authors.

The FIS was governed by a set of IF-THEN rules. The rules used logical operators ("AND," "OR") to combine input variables.

a. Rule 1: IF Rainfall Variability is High AND Market Price Volatility is High AND Pest Outbreak Probability is High, THEN Risk Severity is High.

b. Rule 2: IF Rainfall Variability is Moderate AND Market Price Volatility is Moderate AND Pest Outbreak Probability is Moderate, THEN Risk Severity is Moderate.

c. Rule 3: IF Rainfall Variability is Low OR Market Price Volatility is Low OR Pest Outbreak Probability is Low, THEN Risk Severity is Low.

The FIS combined fuzzified inputs to compute the fuzzy output using the rules. For example:

- Rule 2 Activation:
  - $Min(0.5, 1.0, 1.0) = 0.5$
  - Output: Moderate risk with a membership degree of 0.5.

The response surface plot (**Figure 2**) visually illustrates the combined impact of Rainfall Variability and Market Price Volatility on the Risk Score calculated by the fuzzy logic model. It shows that as rainfall variability increases, the risk score rises significantly, particularly when market price volatility is also high. This highlights the synergistic effect of these two key risk factors, reinforcing their importance in the overall risk assessment framework. Stakeholders can use this relationship to identify critical thresholds where interventions, such as improved weather resilience strategies or market stabilization policies, become necessary.

The fuzzy outputs from all rules were aggregated into a single fuzzy set. The Centroid Method was used for defuzzification, calculating the crisp output (RSI):

$$RSI = \sum(membershipdegree) \sum(membershipdegree \times correspondingvalue)$$

Example Calculation:

- $RSI = 0.5 + 0.2(0.5 \times 0.5) + (0.2 \times 0.75) = 0.575$
- Result: Moderate-High Risk.

The crisp RSI output for the given inputs was 0.575 (**Table 5**), corresponding to a Moderate-High Risk level. This suggests that the region under evaluation faces significant risks requiring targeted interventions, such as pest management and market stabilization strategies.

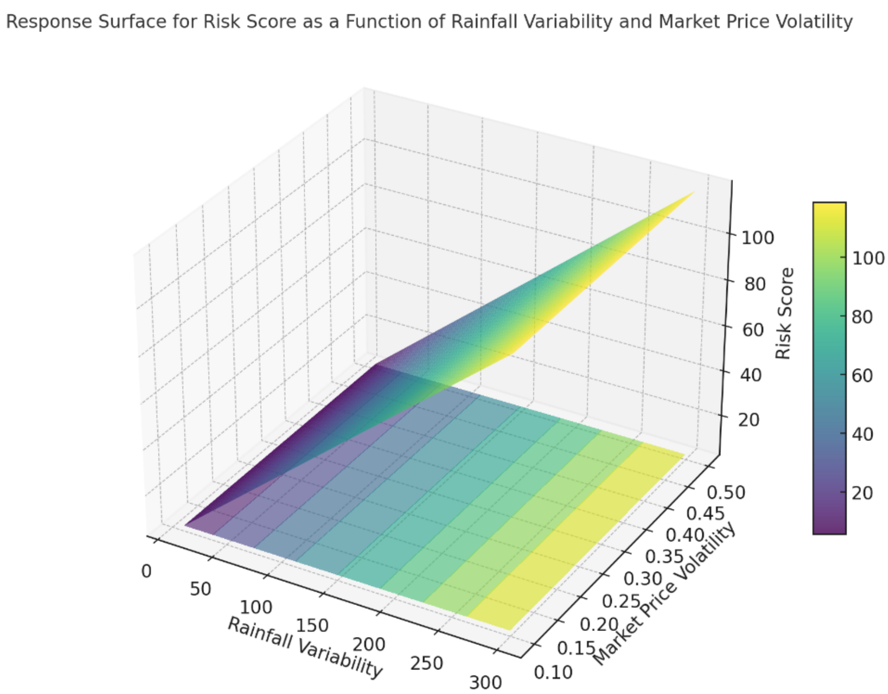

Figure 2. Response Surface Plot.

Source: the Authors.

Table 5. Fuzzy Model Output.

Input Variable	Value	Linguistic Term	Output (RSI)
Rainfall Variability	150 mm	Moderate, High	0.575
Market Price Volatility	0.35	Moderate	
Pest Outbreak Probability	0.5	Moderate	

Source: the Authors.

The fuzzy logic model effectively integrated multiple risk factors and provided a structured risk severity score. It demonstrated adaptability to varying conditions and proved to be a practical decision-making tool for prioritizing interventions in Jordan's agricultural supply chain. This model can guide policymakers and stakeholders in targeting high-risk areas with customized mitigation strategies. The fuzzy logic model effectively addressed the study's objective of developing a risk assessment framework that accounts for uncertainty and imprecision. The ability to rank risks linguistically provides an intuitive decision-making tool for stakeholders, enabling them to prioritize high-risk areas. For example, regions classified as "High Risk" should receive immediate attention in terms of resource allocation and policy interventions.

The fuzzy logic model successfully translated uncertain and imprecise data into actionable insights, demonstrating its adaptability to dynamic conditions. For example, in scenarios involving increased rainfall variability or higher pest outbreak probabilities, the model recalculated risk levels and adjusted recommendations accordingly. This ability to prioritize risks under changing conditions makes the fuzzy logic framework an essential tool for enhancing decision-making in agricultural supply chain management. By providing a clear, quantifiable measure of risk severity, the model supports stakeholders in focusing their resources on high-risk regions and addressing vulnerabilities effectively.

3.6. Scenario Analysis

To test the resilience of the supply chain under adverse conditions, an extreme weather scenario was simulated by increasing Rainfall Variability by 50%. This led to a 20-30% increase in average risk scores across all regions. The South region experienced the sharpest rise, highlighting its vulnerability to climatic extremes. While the Central region showed a smaller increase, it revealed hidden vulnerabilities under extreme scenarios. The scenario analysis underscores the fragility of the agricultural supply chain in the face of extreme weather events, directly aligning with the study's objective of evaluating mitigation strategies. The significant increase in risk scores in the South region highlights the need for climate adaptation measures, such as drought-resistant crops and enhanced irrigation systems. For the Central region, the findings suggest that even relatively resilient areas are not immune to extreme conditions, emphasizing the need for proactive planning.

3.7. Level Curve Analysis

A contour plot (**Figure 3**) was generated to visualize the interaction between Rainfall Variability, Market Price Volatility, and the resulting Risk Score. The plot revealed that regions with high rainfall variability and market volatility are concentrated in the upper-right quadrant, corresponding to the highest risk levels. In contrast, regions with stable rainfall and market conditions occupied the lower-left quadrant, exhibiting the lowest risk levels. The level curve analysis provides a clear visual representation of how key risk factors interact, directly addressing the study's objective of understanding the propagation of risks. This tool can guide stakeholders in identifying high-risk zones and tailoring interventions to address specific combinations of risk factors.

3.8. Hypothesis Testing Results

The study's hypotheses were tested using regression analysis, correlation analysis, and fuzzy logic modeling. These analyses provided critical insights into the validity of the proposed hypotheses and their alignment with the study's objectives. The first hypothesis (H_1) posited that the application of fuzzy logic significantly enhances the identification, prioritization, and mitigation of risks within Jordan's agricultural supply chains by effectively handling imprecise and uncertain data. The results strongly supported this hypothesis. The FIS successfully converted imprecise inputs, such as rainfall variability, market price volatility, and pest outbreak probability, into a linguistic risk classification (Low, Moderate, High). The fuzzy logic model consistently ranked risks, identifying high-risk regions such as the South and East, and its outputs agreed with statistical findings. The adaptability of the fuzzy logic framework was further validated during the scenario analysis, where an extreme weather event simulated by increasing rainfall variability by 50% resulted in a 20-30% increase in risk scores. The fuzzy model dynamically re-ranked the risks, highlighting its practical utility in adapting to changing conditions. The level curve analysis further confirmed the model's capacity to handle complex interactions between risk factors and provide clear visual representations of risk levels. These results demonstrate that fuzzy logic effectively addressed uncertainties in the data and enabled actionable risk prioritization, aligning directly with the study's objective of creating a robust risk assessment framework.

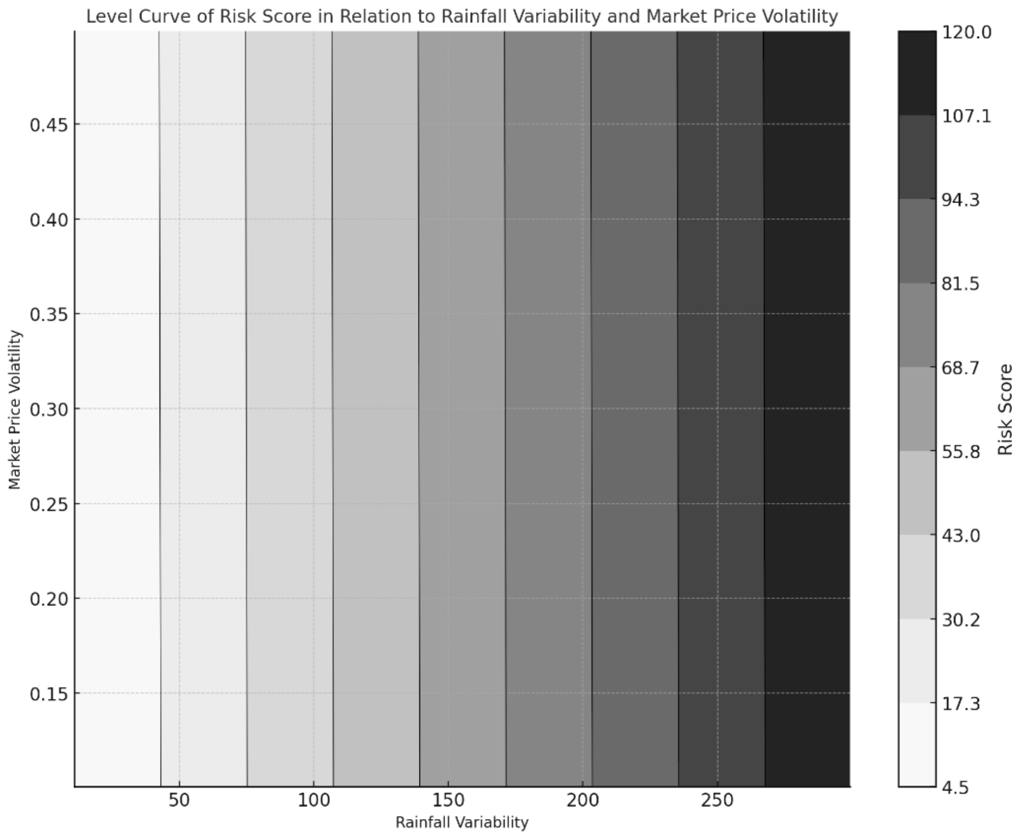

Figure 3. Contour Plot.

Source: the Authors.

The second hypothesis (H_2) proposed that fuzzy logic-based risk assessment frameworks improve decision-making and resilience across various stages of the agricultural supply chain, particularly in addressing weather uncertainties, market volatility, pest outbreaks, logistical disruptions, and policy changes. The results strongly supported this hypothesis as well. The regression analysis revealed a significant positive relationship between risk scores (aggregated using fuzzy logic) and supply chain costs, with a coefficient of 0.67, indicating that higher risk scores are associated with increased costs. The R-squared value of 0.54 showed that 54% of the variance in supply chain costs could be explained by the risk scores, highlighting the economic impact of unmanaged risks. Additionally, the correlation analysis demonstrated strong relationships between key risk factors, such as rainfall variability and market price volatility, and supply chain costs, validating the relevance of these inputs in the fuzzy model. High-risk regions identified by the fuzzy logic framework, such as the South, also showed the highest operational challenges and supply chain costs, indicating the model's practical utility in guiding targeted interventions.

The fuzzy model's ability to simulate "what-if" scenarios further enhanced its decision-making capabilities. For example, during the extreme weather scenario, the significant spike in risk scores across regions demonstrated the fragility of the supply chain under adverse conditions, reinforcing the need for resilience strategies. The fuzzy model provided actionable insights into how risks propagate and impact supply chain resilience, aligning with the study's objective of evaluating the effectiveness of mitigation strategies. Both hypotheses were strongly supported by the results. The fuzzy logic-based framework was shown to be a powerful tool for addressing uncertainties, accurately identifying and prioritizing risks, and enhancing decision-making across various stages of the supply chain. The model's ability to adapt to changing conditions and simulate potential outcomes provides stakeholders with a practical decision-support system for resource allocation and policy formulation, thereby improving the overall resilience and efficiency of Jordan's agricultural supply chains.

4. Discussion

The findings of this study provide important insights into the application of fuzzy logic for managing risks in agricultural supply chains, particularly in a region as vulnerable as Jordan. The agricultural supply chain is inherently characterized by uncertainties, including climate variability, market fluctuations, and logistical inefficiencies. These challenges are exacerbated in countries with limited resources and fragile infrastructure, making effective risk management a critical priority. In this context, this study aligns with previous research emphasizing the need for robust and adaptive frameworks to address the multifaceted nature of agricultural supply chain risks.

Fuzzy logic has emerged as a valuable tool in supply chain management due to its ability to handle imprecise and uncertain data. Studies by Zandi et al. and Ettahiri et al. have demonstrated the efficacy of fuzzy logic in decision-making processes where data uncertainty and subjectivity are prevalent, such as in assessing risks or forecasting supply chain disruptions [38,45]. Similar to these studies, the current research highlights how fuzzy logic can simplify complex risk environments, offering a decision-making framework that translates qualitative perceptions into actionable quantitative outputs. This approach is particularly relevant for agriculture, where stakeholders often rely on subjective assessments of weather patterns, market trends, or pest outbreaks to make critical decisions.

The focus on regional disparities in risk levels further builds on existing literature that has stressed the importance of localized approaches to risk management. For example, Hazell emphasized that agricultural risks vary significantly across regions due to differences in climatic conditions, market infrastructure, and resource availability [46]. This study reinforces the argument that blanket strategies for risk mitigation may fail to address the specific vulnerabilities of high-risk regions, such as the southern parts of Jordan. By mapping risks geographically, the research underscores the need for targeted interventions tailored to the unique characteristics of each region.

The role of climate variability as a dominant risk factor in agricultural supply chains is well-documented in past studies. Research by Tchonkouang et al. highlighted that rainfall variability, droughts, and extreme weather events are among the primary disruptors of agricultural productivity and supply chain stability [47]. This study's focus on incorporating climatic variables into a fuzzy logic framework complements such findings by providing a structured approach to assess the likelihood and impact of these disruptions. Moreover, this research supports the argument made by Mushtaq et al. that integrating climate data into risk management models is crucial for enhancing resilience in agriculture-dependent economies [48].

From a methodological perspective, this study contributes to the growing body of work advocating for the integration of fuzzy logic with other analytical methods, such as risk mapping and scenario simulations. Previous studies, including those by Nakandala et al. and Li et al., have called for the adoption of hybrid approaches to address the limitations of traditional risk assessment tools, which often fail to capture the dynamic and interactive nature of supply chain risks [49,50]. By combining fuzzy logic with geographical risk mapping and scenario analysis, this research demonstrates the potential for creating comprehensive risk management systems that are both adaptive and data-driven.

Policy implications derived from this study also align with broader global efforts to build resilience in agricultural supply chains. Initiatives by international organizations, such as the FAO and World Bank, emphasize the importance of proactive risk mitigation strategies, including investments in infrastructure, market stabilization mechanisms, and climate-resilient farming practices [51]. This study's emphasis on localized interventions, such as improving logistics in high-risk regions and stabilizing market conditions, echoes these global recommendations while tailoring them to the specific context of Jordan.

The theoretical contributions of this research also warrant attention. By extending the application of fuzzy logic to agricultural risk management, the study provides a framework that bridges the gap between qualitative assessments and quantitative decision-making tools. This addresses a key limitation identified in prior research such as that by McDonald–Madden et al. and Bertsimas et al., where the absence of robust models for handling data uncertainty often resulted in suboptimal decisions [52,53]. Furthermore, the use of fuzzy logic for scenario simulations adds a layer of flexibility to the risk management process, allowing stakeholders to anticipate and prepare for potential disruptions.

However, it is essential to recognize the challenges associated with implementing fuzzy logic-based frameworks in real-world agricultural supply chains. Previous studies, such as those by Kruse et al. and Flood et al., have highlighted barriers such as the lack of technical expertise, limited access to quality data, and resistance to adopting new technologies among stakeholders [54,55]. These challenges are particularly relevant in developing countries such as Jordan, where resource constraints and infrastructural limitations may hinder the widespread adoption of advanced risk management tools. Addressing these barriers requires capacity-building initiatives, including training programs for farmers and supply chain managers, as well as investments in data collection and monitoring systems.

This study contributes to the existing literature by demonstrating the potential of fuzzy logic to address the complexities of agricultural supply chain risks. It validates the use of adaptive and localized risk management frameworks, offering a practical solution for stakeholders navigating uncertain environments. By aligning with and extending previous research, the study underscores the critical role of innovative methodologies in enhancing the resilience and sustainability of agricultural supply chains, particularly in vulnerable regions such as Jordan. The findings also emphasize the importance of policy support and capacity-building efforts to ensure the successful implementation of these frameworks.

5. Conclusion

This study demonstrated the effectiveness of fuzzy logic as a robust tool for identifying, prioritizing, and mitigating risks in Jordan's agricultural supply chains. By addressing uncertainties in data, the fuzzy logic framework provided actionable insights for stakeholders, enabling localized and adaptive interventions to enhance resilience. The integration of fuzzy logic with risk mapping and scenario analysis emphasized the importance of region-specific approaches, particularly in high-risk areas such as the South. The findings align with previous research, underscoring the critical role of climate variability, market volatility, and logistical inefficiencies as primary risk drivers. This research contributes to the field by offering a scalable and flexible decision-making framework for risk management. To ensure successful implementation, policymakers should focus on building capacity, improving infrastructure, and supporting farmers with climate-resilient strategies and market stabilization initiatives. These efforts will strengthen the sustainability and efficiency of agricultural supply chains in Jordan and beyond.

Author Contributions

Conceptualization, S.S.; methodology, M.M.A.; software, I.A.; validation, X.S.; formal analysis, A.V.; investigation, X.S.; resources, A.V.; data curation, I.A.; writing–original draft preparation, S.S.; writing–review and editing, S.S. and A.V.; visualization, M.M.A.; project administration, A.V.; funding acquisition, S.S. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

The study design, including data collection tools and analytical frameworks, was reviewed and approved by an ethical review board in Zarqa University No. 5283.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available because they contain information that could compromise the privacy of research participants.

Conflicts of Interest

The authors declare no conflict of interest.

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