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Assessment of External Vulnerability of Rice Supply Chain Using FMEA, Bishwanath Upazila, Sylhet, Bangladesh

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Abstract:

The supply chain is a complex system that flows from raw materials into an end product and service through multiple stages including production, manufacturing, distribution etc. Rice is a staple crop with high per capita consumption in Bangladesh. As the country experiences rapid economic growth, the socioeconomic and environmental conditions require effective management of the rice supply chain to ensure economic stability and food security. However, severe flooding and challenges related to environmental variability as well as complex chain systems worsen chain vulnerability. This study focuses on the Bishwanath upazila in the Sylhet district heavily impacted by recent floods. A field survey was conducted along with 167 randomly selected household surveys along with Key Informant Interviews (KII) and in-depth Interviews (IDIs), as well as three Focused Group Discussions (FGDs). The study employed Failure Mode and Effect Analysis (FMEA) to identify and mitigate risks. In accordance with the FMEA approach, vulnerable modes across 7 stages including production, harvesting, processing, transportation, storage, distribution, and consumption were observed. The approach found that flooding, pest infestations, and drought were major issues with flooding having the most severe impact on crop production. On the other hand, consumption was the least impacted stage among the 7. The local adaptive measures were found to be insufficient leading to the development of a resilience framework. The framework recommended flood-tolerant rice varieties like Swarna Sub1 and Ciherang SUB1 which can improve yields by up to 19%. Moreover, the resilience framework focused on applying technology and using renewable energy.

Keywords: Supply chain, FMEA, vulnerability assessment, resilience framework.

1. Introduction

The supply chain encapsulates the total process of transforming raw resources into products and ultimately a service. It is an intricate system that involves multiple stages, including sourcing materials, manufacturing, logistics and distribution, working together to deliver value to the eventual customer. Now, this system can be made up of various companies each performing a different role to aid the system such as suppliers, manufacturers, logistics providers, and distributors or of different sectors working together to provide a single service, or even a mixture of both. Such complexities of a system with a vast scope need management to ensure effective coordination, efficiency, and alignment with central goals. This management is termed Supply Chain Management (SCM), a term that gained prominence when Keith Oliver, a consultant at Booz Allen Hamilton, coined the term during a 1982 Financial Times interview (Roy & Roy, 2013). Four decades later, the term provides a critical introspection into the world of supply and consumption to ensure effective implementation of all operations and identify factors that impact the system and ultimately make it susceptible to vulnerabilities.

Bangladesh is one of the fastest growing nations, claiming its position as the third highest in the world (Azad, 2023). This rapid economic development is actively impacting our unique socio-economic and environmental conditions, bringing forth changes in all sectors of the supply chain. As a result, the already complex system of supply chain becomes more complex due to issues such as environmental variability and logistical constraints. These factors contribute to the intricacies of managing and optimizing the supply chain as they affect various aspects of economic and social infrastructure. The change is also noticed in the trend of the sectorial share of GDP, where for the fiscal year of 2021 the contributions of agriculture, industry and services were 12.1%, 33.9% and 54% respectively (Azad, 2023). It is evident that while agriculture remains a huge part of the economy, it is moving towards a more industrialized and export-based one. Nonetheless, Bangladesh is at its heart an agrarian nation with many still upholding the traditional practices of farming while incorporating modern aids.

Rice is one of the major crops of Bangladesh with high per capita consumption of rice (Shelley et al., 2016). Over the years, with ever increasing population, the cultivation and yield of rice have increased as well. However, it is also vulnerable to and marred by environmental variabilities and climate change. One such condition can be well observed in Bishwanath Upazila of Sylhet district, the research area.

Situated between 24°44' and 24°56' north latitudes and between 91°39' and 91°50' east longitudes, Bishwanath upazila is enclosed by Sylhet Sadar and Chhatak upazilas on the north, Balaganj upazila on the south, Dakshin Surma upazila on the east and Jagannathpur and Chhatak upazila on the west (Bangladesh Bureau of Statistics, 2001, 2007, 2011). The upazila is home to the Surma River and Konaura, Naldubi and Chaulbuni beels. Due to the geospatial positioning of Bishwanath Upazila and the presence of the Surma River which is flood-prone in monsoon, the upazila is quite vulnerable to flooding and the resultant waterlogging. Such vulnerability is exacerbated by climate change as evidenced by the consecutive flooding of the recent years from 2022 to 2024. As a result, rice cultivation becomes somewhat difficult and leads to less yield (Dey et al., 2023). According to the US Department of Agriculture, rice cultivation particularly of Aus has suffered loss due to flood in Sylhet and as well as has yielded 2.05 million tones countrywide against the projected target of 2.7 million tons for the fiscal year of 2021-22 (U.S. Department of Agriculture, Foreign Agricultural Service, 2024). Aside from the loss of yield, flooding and waterlogging also halt and damage the transportation and logistics systems of the upazila.

Consequently, the geographical location of Bishwanath Upazila poses several challenges to multiple stages of the rice supply chain such as production, harvesting, transportation, storage, market prices, and ultimately consumption while also exposing the chain to various factors of vulnerability. Besides, supply chains are prone to suffer from irregularities stemming from a lack of transparency involving parties from each stage (Chowdhury et al., 2023). All these factors together make the supply chain vulnerable to disruptions, inefficiencies, and potential losses at various stages.

When relating disruptions to supply chain vulnerability, it is important to concentrate on nodes of failure which can pose significant threats to that supply chain (Blackhurst et al., 2018). Aside from nodal failure, the length and complexity of supply chains as well as specific practices adopted by firms also increase the vulnerability of the supply chain (Sharma et al., 2023). With the era of globalization and the global marketplace, the chains keep on getting lengthy and ever complex, as a result, it is difficult to avoid vulnerabilities from disrupting the chain. However, there should remain a balance, an equilibrium of vulnerability and risk within the chain (Asbjørnslett, 2009). There are several dynamic approaches to vulnerability assessment that can be tailored to a particular supply chain aiming to balance vulnerability reduction with increased resilience (Elleuch et al., 2016).

In the context of Bangladesh, supply chain assessments are usually done in connection to SCM or the RMG (Ready Made Garment) sector (Ali & Habib, 2012; Hossain & Roy, 2016; Ullash et al., 2023; Anam et al., 2023; Islam et al., 2023). Research on the rice supply chain is generally centered around the modelling or milling industry (Hossain & Jahan, 2018; Bala et al., 2017; Putro et al., 2022). More research is required to address the specific vulnerabilities and inefficiencies within the rice supply chain which is essential to food security.

The study employs the FMEA (Failure Mode and Effect Analysis) approach to ascertain vulnerability factors of the rice supply chain. The approach helps in determining potential risks that might occur (Stamatis, 2003). The approach has been shown to be instrumental in enhancing the capability of risk management for the rice supply chain (Zandi et al., 2020). Utilizing FMEA, this research aims to identify and assess vulnerabilities within the rice supply chain. The specific objectives are:

i. To identify vulnerable factors within the rice supply chain.

ii. To analyse and compare the vulnerability of different stages of the supply chain.

iii. To provide a resilient framework for effective operation of the supply chain.

2. Methods

The present study has been conducted in the Bishwanath upazila of Sylhet district as the district has been facing more disastrous floods in recent periods. The total area of Bishwanath Upazila is 213.16 square kilometers, which is situated between latitudes 24°44' and 24°56' north and longitudes 91°39' and 91°50' east. It is enclosed to the north by the upazilas of Sylhet Sadar and Chhatak, to the south by Balaganj, to the east by Dakshin Surma, and to the west by the upazilas of Jagannatthpur and Chhatak. (Bangladesh Bureau of Statistics, 2001, 2007, 2011). The study area was purposefully chosen because of the intensity of flood disasters, accessibility to the locality, and using insights gathered from various sources, including newspapers, existing reports, literature reviews, and expert opinions.

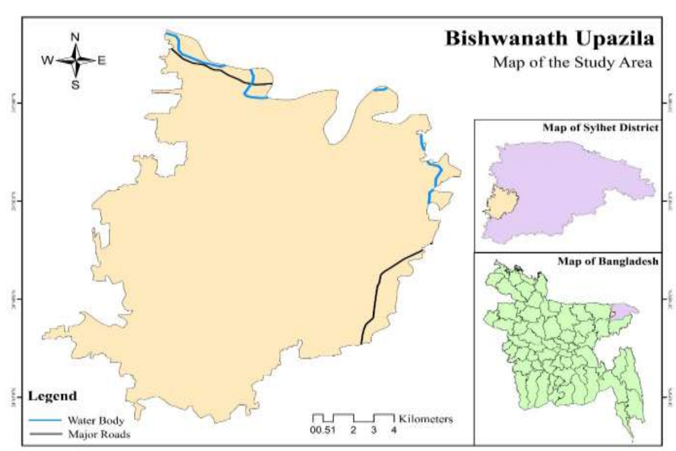

Figure 1: Study Area (Source: prepared using ArcGIS 10.5).

This empirical study has been conducted using extensive field research and sampling, extracted from both retail and wholesale rice stores and households as well. In total 167 households of farmers, retail, and wholesale stores from the entire Bishwanath upazila have been chosen randomly for the survey using specialized questionnaires for different stages. Nearly 80% of the respondents were male and between the ages of 20 and 70. The respondents were chosen based on their status as the head of the family. Being a country predominated by males, the male head of the household is the best person to ask about the flood disaster phenomenon in this region as he is familiar with it personally. (Hossain et al., 2020)

Complementary approaches such as key informant interviews (KII) and in-depth interviews (IDI) were conducted to gather a vast amount of valuable insights, perspectives, individual experiences, and attributes from people who were knowledgeable about flood disasters, including agriculture officers in the upazila level, seed suppliers, local traders, climate experts, community leaders, members of the Union Parishad, representatives of GOs as well as experts from NGOs for the better understandings of this qualitative research. On the other hand, a total 3 focus group discussions (FGD) (containing 6-12 participants in each group) have been held at the upazila level using a pre-assigned checklist to identify the effects of flooding and the people's coping mechanisms in the event of such a catastrophic situation.(Hossain et al., 2020)

Additionally, this study has relied on the ethnographic observation method to gain a deeper understanding of the viewpoints of the respondents with deeper observation and engagement with the respondents in their actual situations.(Hossain et al., 2020) Lastly, interview sessions were carefully examined and analyzed considering the study's goals using the Failure Mode Effect Analysis (FMEA) approach.(Indrasari et al., 2021)

In this approach failure modes have been examined in 7 stages, these are- production, harvesting, processing, transportation, storage, distribution, and consumption. Each stage has been examined through different questionnaires by interviewing individuals purposively predetermined according to their expertise level and the overall goal of the study.

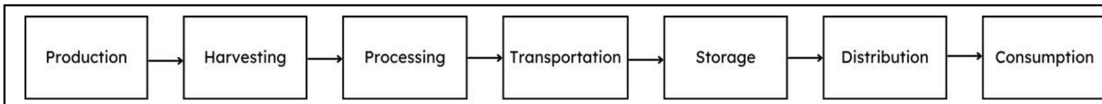

Figure 2: Stages of Rice Supply Chain.

A total of 57 individuals were interviewed together for both the production and harvesting stages, 23 for the processing stage, 17 for the transportation stage, 3 for the storage stage, 18 at the distribution stage, and 49 at the consumption stage. The number of interviewees has been determined randomly and purposely depending on their location of action, relevance to the study, and availability during the survey. The Failure Mode and Effect Analysis approach will be used to examine any elements in the supply chain that may obstruct the full process and lead to complexities in the rice market. This approach has three related factors as- Severity (S), Occurrence (O), and Detection (D). The Risk Priority Number (RPN) in Table 2 below will be calculated using these 3 factors with the equation below: (Indrasari et al., 2021)

$$R\ P\ N = S \times O \times D \ldots\ldots\ldots\ldots\ldots \quad (1)$$

Later these factors have been transformed into ones that can be applied to the Supply Chain Management process after the computations are completed. Considering the following table 1 and figure 3:

Table 1: Risk Priority Number (RPN).(Shamseddin Alizadeh et al., n.d.).

R P N	**Condition**

1-100	Low Risk
101-250	Moderate Risk
251-500	High Risk
More than 500	Critical Risk

Hazardous without warning	10	10 Very high: Failure is almost inevitable	10	Cannot detect
Hazardous with warning	9		9	Very remote chance of detection
Loss of primary function	8	8 High: Repeated failures	8	Remote chance of detection
Reduced primary function performance	7		7	Very low chance of detection
Loss of secondary function	6	5 Moderate: Occasional failures	6	Low chance of detection
Reduced secondary function performance	5		5	Moderate chance of detection
Minor defect noticed by most customers	4		4	Moderately high chance of detectio
Minor defect noticed by some customers	3	3 Low: Relatively few failures	3	High chance of detection
Minor defect noticed by discriminating customers	2		2	Very high chance of detection
No effect	1	1 Remote: Failure is unlikely	1	Almost certain detection

Figure 3: FMEA risk priority number scale. (Roessingh & Kist, 2016).

Finally, the qualitative research has been conducted together with the help of MS Excel, and IBM Statistical Package for Social Science (IBM-SPSS) version 20 software to analyze collected data. To avoid any kind of overlaps or inconsistencies, secondary data were examined and reviewed thoroughly.

Research Framework

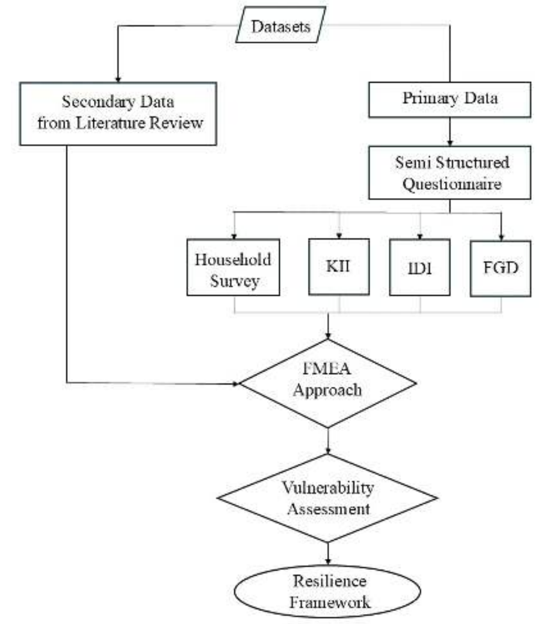

Figure 4: Framework of the study.

3. Results and Discussion

In the context of improving the rice supply chain, it is necessary to understand the current conditions of the supply chain process. This research provided a foundation for recognizing the factors causing obstructions and areas of advancement essential to enact the convenient sustainability goals using the "Failure Mode and Effect Analysis (FMEA)".

An outline of specific strategies has been provided by this study which aimed at mitigating the comprehensible risks and elaborating on the resilience and sustainability of the rice supply chain. Additionally, the research supplied a greater comprehension of managing the supply chain in the agricultural sector, introducing insights into the challenges and assets within the context of Bishawanath Upazila, Sylhet.

Potential failure modes at each stage and their significance for the rice supply chain have been identified in the following analysis. Additionally, strategic mitigation measures to address these issues are also proposed. How proactive strategies can ensure the continuous improvement of the rice supply chain is also emphasized here.

Table 2: identification of failure modes

Stage	Failure Mode	Cause	Code
Production	Flood	Heavy rainfall, poor drainage	A1
	Drought	Extended dry periods, inadequate irrigation	A2

	Pest Infestation	Climate change, lack of pest control	A3
	Disease Outbreaks	Favorable conditions for disease pathogens	A4
Harvesting	Weather Variability	Unpredictable weather conditions	B1
	Labor Shortages	Seasonal migration, economic factors	B2
Processing	Power Outrages	Unreliable power supply	C1
	Infrastructure Damage	Extreme weather events	C2
Transportation	Poor Road Conditions	Heavy rains, lack of road maintenance	D1
	Fuel Price Fluctuations	Global fuel price changes	D2
Storage	Humidity and Temperature	Poor storage conditions	E1
	Pet Infestation	Inadequate pest control	E2
Distribution	Market Access	Extreme weather, road damage	F1
	Regulatory Changes	New regulations or trade restrictions	F2
Consumption	Price Volatility	Supply chain disruptions	G1
	Supply Chain Disruptions	Failures in earlier stages	G2

A comprehensive overview of the potential failure modes identified at each stage of the rice supply chain and their causes is presented in Table 2. These failure modes are experienced by the stakeholders at different stages. After finding out the problems faced by the stakeholders, an analysis of the effects due to failure modes arising in Table 3 from the different stages has been carried out as follows.

Table 3: Risk arising due to failure modes

Risks arising from problems	Code
Crops loss, reduced yield	R1
Water scarcity, reduced crop growth	R2

Crop damage, reduced yield	R3
Reduced yield, crop damage	R4
Delayed harvesting, crop damage	R5
Delayed harvesting, increased labor costs	R6
Disruption of milling operations	R7
Disruption in processing, increased costs	R8
Delayed transportation, increased costs	R9
Increased transportation costs	R10
Spoilage, quality degradation	R11
Inadequate pest control	R12
Isolation of markets, disrupted distribution	R13
Impact on distribution practices and costs	R14
Increased consumer prices, reduced access	R15
Shortages, increased prices	R16

After knowing the risk arising due to failure modes, a Factor Mode and Effect Analysis approach was executed to determine the severity of the current supply chain process in this study area. Then the outcomes of Failure Mode and Effect Analysis are as follows:

CD- Code of discovery of problems, CR- Code of risk that occurs

Table 4: Calculation of RPN and RANK

NO	CD	CR	S (1-10)	O (1-10)	D (1-10)	RPN	RANK
1	A1	R1	9	8	5	360	1
2	A2	R2	7	6	6	252	3
3	A3	R3	8	7	5	280	2
4	A4	R4	7	6	5	210	6
5	B1	R5	8	6	5	240	4
6	B2	R6	6	6	5	180	12

7	C1	R7	8	4	6	192	11
8	C2	R8	7	5	5	175	13
9	D1	R9	8	6	5	240	5
10	D2	R10	7	5	6	210	7
11	E1	R11	8	5	5	200	8
12	E2	R12	7	6	4	168	14
13	F1	R13	8	5	6	240	6
14	F2	R14	7	4	5	140	16
15	G1	R15	8	5	5	200	10
16	G2	R16	7	6	4	168	15

After gaining knowledge of the calculation results in Table 4 of the Failure Mode and Effect Analysis, ranking 1 became acquired, namely Code A1 (flood) in this example has been affecting the manufacturing of rice. According to KI (Key Informant), for the last 3 years, the effect of flooding has crossed the previous year's record. Flood water stays for an extended length. Flood water washes away topsoil which results in lowering yield. Furthermore, it's also inflicting delays within the planting season. According to the local farmers, they must take mortgages from distinctive banks, and NGOs to restore their damage, and buy new seeds which would ultimately affect their profitability.

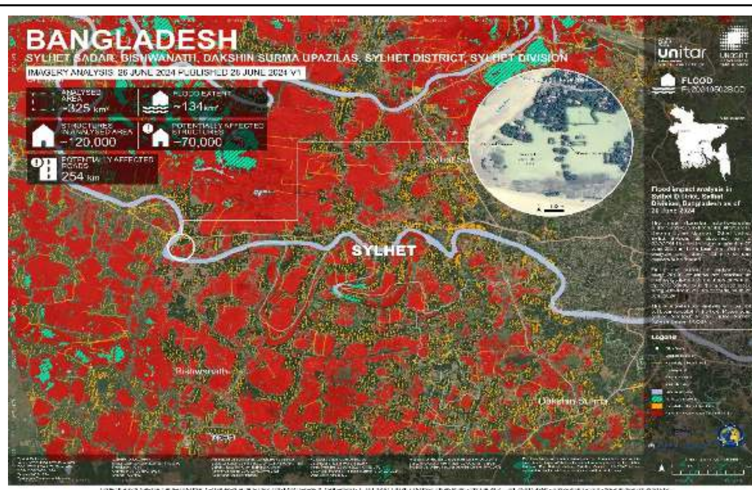

Figure 5: Flood Impact Analysis, Sylhet, source: (UNOSAT_A3_Natural_Landscape_FL20240502BGD_SylhetSadar_Sylhet_Bangladesh_26June2024(1).

The recent flood that occurred in Sylhet and Sunamganj district extended 134 km2 and potentially affected 70,000 structures and 254 km of roads including Bishwanath Upazila (figure 5). Primarily, floods impact the entire supply chain process (crop production, transportation, market fluctuation, etc.) by damaging structures and roads. Ranking 2 and 3 were obtained by code A3 (pest infestation) and A2 (drought) respectively which indicated that the Production stage is the most vulnerable stage due to external factors. For example, (Mwakyusa et al., 2023) in their study identified that, a significant crop losses and disruption of the life of farmers occurred by the flood. They pointed out flood as a commanding aggravation, responsible for 100% yield loses in utmost cases, like vulnerabilities experience in the study area of this research.

Among the 16 problems identified in this research, code F2 (regulatory changes) has less impact than others and the Consumption stage is the least vulnerable stage as price volatility or supply chain disruptions would not affect much the consumption rate.

From in-depth interviews, focus group discussions, and KI, the study figured out- the locally led adaptive measures are not enough to reduce the loss and damage and a smooth supply chain. Therefore, a resilience framework has been developed and proposed. (table 5). In this framework, modern technology, IoT, and policy-level engagement were focused on. (Michael et al., 2023) in their study emphasized that advanced technology is must to enhance resilience. They also showed the importance of flood tolerant rice varieties. Two such varieties are- Swarna Sub1 and Ciherang SUB1 have enhanced yield by up to 19% in flood affected areas.

Table 5: Current Controls and Resilience Framework

Failure Mode	Current Controls	Resilience Framework	Effect Scale
Flood	Drainage systems, flood-resistant rice varieties, weather forecasting, and early warning systems.	Improved flood defenses (e.g., embankments, levees), advanced drainage systems, GIS-based flood risk mapping.	High
Drought	Drought-resistant rice varieties, rainwater harvesting, irrigation management, soil moisture monitoring.	Efficient irrigation infrastructure, rainwater harvesting, drought-tolerant varieties, and reservoirs for water storage.	High
Pest Infestation	Pest monitoring, IPM practices, pesticide application, biological control.	Precision agriculture technologies (drones, sensors), biocontrol agents, organic farming, and farmer training.	High
Disease Outbreaks	Disease monitoring, fungicide application, disease-resistant varieties, crop rotation.	Genetic engineering for disease-resistant varieties, predictive modelling, biosecurity measures.	High
Weather Variability	Weather forecasting, scheduling, mechanized harvesting.	Mobile weather stations, weather-resilient machinery, flexible labor arrangements.	Medium

Labor Shortages	Recruitment of temporary labor, incentives, mechanized tools, and labor agencies.	Mechanized harvesting, community labor-sharing schemes, and government incentives for rural labor retention.	Medium
Power Outages	Backup generators, alternative energy sources, and infrastructure maintenance.	Transition to renewable energy, advanced energy storage systems, collaboration with energy providers.	High
Infrastructure Damage	Regular maintenance, insurance coverage, temporary structures.	Investment in resilient infrastructure, rapid-response repair teams, and disaster risk management plans.	High
Poor Road Conditions	Road maintenance, alternative routes, transportation scheduling.	Road infrastructure upgrades, alternative transport modes, and real-time monitoring systems.	High
Fuel Price Fluctuations	Fuel-efficient vehicles, route optimization, bulk fuel purchasing, alternative fuels.	Alternative fuel vehicles, fuel hedging strategies, logistics optimization.	Medium
Humidity and Temperature	Climate control systems, storage condition monitoring, moisture-absorbing materials.	Climate-controlled storage facilities, IoT sensors for monitoring, post-harvest management best practices.	High
Pest Infestation (storage stage)	Fumigation, sealed containers, pest control protocols.	Advanced pest control technologies (e.g., pheromone traps), regular inspections, pest-resistant storage designs	High
Market Access	Alternative distribution channels, stockpiles, and collaboration with government agencies.	Development of alternative distribution networks, e-commerce platforms, and road repair partnerships.	High
Regulatory Changes	Monitoring regulatory updates, engagement with policymakers, and compliance audits.	Active policy engagement, agile business practices, regular compliance audits	Medium
Price Volatility	Price stabilization mechanisms, government subsidies, strategic reserves.	Long-term supplier contracts, demand forecasting tools, and price stabilization strategies.	Medium
Supply Chain Disruption	Diversified supply sources, contingency planning, and advanced forecasting.	Diversification of suppliers, contingency plans, crisis management teams, and digital supply chain platforms.	High

A comparison between the existing measures and proposed enhanced resilient strategies for each failure mode across the rice supply chain is shown in Table 5. The Potential impact of these resilient measures on improving the supply chain's stability and mitigating risks have been indicated by the effect scale.

5. Conclusion

This study provides a comprehensive assessment of risks that the rice supply chain in Bishwanath Upazila, Sylhet, Bangladesh is exposed to by postulating key failure points and their implications. The FMEA analysis suggested that climatic variables such as flood and drought significantly influence all steps along the supply chain process. As a result, the results indicated that defenses had to be robustly implemented. Recommendations ranged from adaptive agricultural technologies to improved infrastructure and early warning systems. Furthermore, these measures can be made more sustainable through policy alignment. Nonetheless, some limitations exist for this study which should be kept in mind including geographical focus and precision of analyzed climate variables. In future research, there is a need to consider large regional assessments, market dynamics, and socio-economic factors to address any biases at different levels of the system. Overall, these results contribute knowledge on external vulnerabilities along rice supply chains as well as establish a basis for enhancing strategies towards resilience and sustainability under climate change.

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