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Comprehensive risk management in agricultural supply chains: strategies and approaches - case of Persian lime in Veracruz

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Abstract: The Agri-Food Supply Chain (AFSC) is essential for global food supply, economic development, and employment. However, it faces significant risks that undermine its efficiency, mainly due to the perishability of its products, which complicates risk management. Despite its importance, research on risks in this sector, especially for specific agricultural products, remains limited. This study addresses this gap by identifying, evaluating, and prioritizing risks in the first link of the Persian Lime (Citrus latifolia Tanaka) AFSC in the Citrus District of Martínez de la Torre, Veracruz, Mexico. Using semi-structured interviews with eleven experts in integrated crop management, 53 risks were identified and categorized into natural, pest, disease, supply, and operational risks. The Decision-Making Trial and Evaluation Laboratory (DEMATEL) technique was applied to analyze cause-effect interactions. At the same time, Failure Mode and Effects Analysis (FMEA) was used to prioritize these risks. The results indicate that pesticide scarcity is the most influential causal risk, while an incidence exceeding 5% of trees affected by gummosis (Phytophthora spp.) has the most excellentmost significant impact. Additionally, high staff turnover was identified as the most critical risk. These findings give decision-makers a robust foundation to develop risk management plans that enhance the AFSC's resilience. Such measures will help ensure a continuous food supply and enable processing and packing companies in the subsequent links to meet demand, thus improving the stability and sustainability of the agri-food system amid long-term disruptions.

1 Introduction

The Agri-Food Supply Chain (AFSC) is a cornerstone of food security, economic development, and employment on a global scale. However, the perishability of its products, combined with production variability caused by climatic conditions and biological processes, makes risk management a complex challenge [1]. Identifying, evaluating, and prioritizing risks is essential for developing effective mitigation and control strategies.

Globally, stakeholders in each link of the supply chain work proactively to manage these risks, ensuring operational continuity and food security. Agri-food exports play a critical role in the economy. For instance, in May 2023, Mexico generated USD 2.13 billion in agricultural and fishing exports, ranking as the world’s 11th-largest food producer, 7th-largest agri-food exporter, and the second-largest lime producer [2]. The Persian Lime AFSC, which primarily targets export markets, is particularly significant. The United States receives most of Mexico’s production, followed by Canada, France, the Netherlands, Germany, Saudi Arabia, the United Kingdom, Japan, and South Korea. However, in recent years, lime cultivation has faced adverse natural events, including extreme weather conditions, pests, diseases, and viruses, as well as operational and supply challenges. Therefore, identifying and assessing these risks is crucial to anticipate and mitigate their effects.

While risk studies in supply chains are abundant, particularly in the manufacturing sector, research in the agri-food sector remains limited, especially for specific agricultural products. This article addresses this gap by identifying, evaluating, and prioritizing risks in the first link (orchard production) of the Persian Lime AFSC in the Citrus District of Martínez de la Torre, Veracruz, Mexico.

Many risks in this sector are interdependent, which makes hierarchical analysis insufficient. While FMEA is valuable, it does not account for causal relationships between criteria. DEMATEL provides a complementary approach by identifying cause-effect relationships and interdependencies. This study employs both techniques to prioritize risks based on their likelihood of occurrence, detection, and impact, supported by insights from eleven experts in Persian Lime integrated crop management.

The results provide a robust foundation for decision-makers to anticipate risks and design mitigation and control plans that strengthen the resilience of the AFSC. These actions will ensure a continuous food supply, meet the demand of processing and packing companies in subsequent links, and enhance the stability and sustainability of the agri-food system amid long-term disruptions.

2 Literature review

2.1 Lime cultivation in Mexico

Mexico's main lime varieties include Mexican lime (*Citrus aurantifolia*), yellow or Italian lime (*Citrus lemon*), and Persian or seedless lime (*Citrus latifolia tanaka*). While Mexican lime is primarily for domestic consumption, Italian and Persian limes are grown for export, with Persian lime dominating in volume and significance. In 2023, Mexico produced 3.2 million tons of lime, with Persian lime accounting for 50.4%. Other producing states contributing to these figures are Jalisco (5.79%), Yucatán (6.58%), and Oaxaca (12.91%). Veracruz, particularly Martínez de la Torre, contributed 31.89% of the 53.04% of Persian lime produced in the state, making it a key player in the industry [3].

2.2 The Persian lime AFSC

Martínez de la Torre, located in northern Veracruz, Mexico, is bordered by municipalities such as Papantla, Tecolutla, San Rafael, Atzalan, Misantla, Tlapacoyan, and San José Acateno. Its geographical location and soil-climatic conditions make it ideal for Persian lime production, with the fruit meeting the quality standards for export to Europe and Asia. Known as "The World Capital of Persian Lime" the region exports to countries such as the United States, Canada, France, the Netherlands, Germany, Saudi Arabia, the United Kingdom, Japan, and South Korea. The United States is the primary destination for these exports.

The Persian lime AFSC in Martínez de la Torre has three main links as shown in Figure 1. The first involves orchard production (suppliers), the second includes processing and packing facilities, and the third covers commercialization.

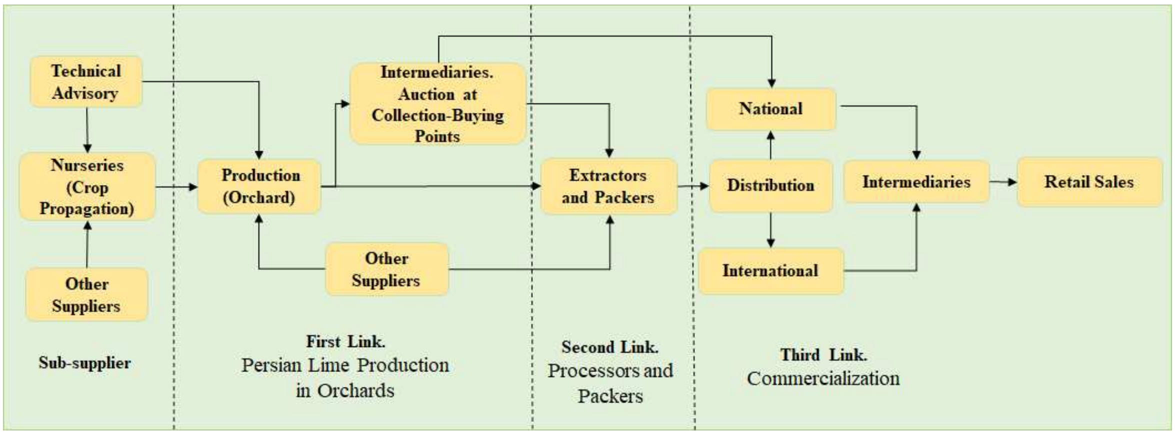

Figure 1 Supply chain of Persian lime

This supply chain represents a significant economic pillar for the district and the country, as it generates numerous direct and indirect jobs across its various stages. However, in recent years, the cultivation of Persian lime has been adversely affected by climatic events that exacerbate other challenges, such as pests, diseases, and viruses, as well as operational issues. These risks must be identified and assessed proactively to anticipate and mitigate their impact.

2.3 Risk management

Risk, in general, refers to the possibility of an undesirable event occurring that has the potential to cause harm. Within the Supply Chain (SC)pertains to uncertain events or conditions that negatively impact the objectives of businesses across its various stages. Risks are categorized asInternal risks, which arise within the company or SC and include supply, process, demand, logistics, financial, and collaboration risks. External risks stem from outside the SC and encompass natural risks[4]. Identifying and managing risks is crucial to reducing vulnerability and strengthening the SC's resilience [5]. Furthermore, it fosters a risk management culture as a comprehensive business strategy across the entire chain [6].

2.4 Techniques for RiskRisk management

SC risk management is typically divided into four key phases: identification, evaluation, treatment, and monitoring [7,8]. These stages provide a systematic approach to addressing potential threats and ensuring the SC's resilience. The structure of these phases is visually summarized in Figure 2.

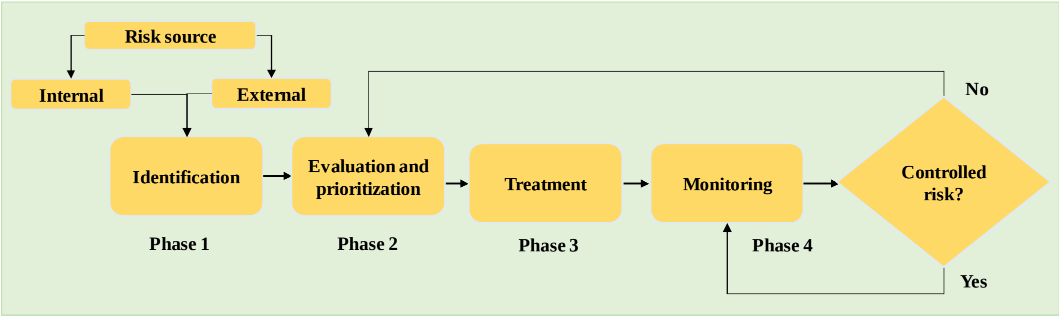

Figure 2 Methodology for risk management (based on [7,8])

2.4.1 Risk identification

The first phase involves pinpointing potential risks that could affect the SC. Techniques such as checklists, event tree analysis, fault tree analysis, Ishikawa cause-and-effect diagrams, and FMEA are commonly employed [8]. Brainstorming sessions and expert interviews are also helpful, though they face the limitation of struggling to anticipate unprecedented events [9].

2.4.2 Risk evaluation

Risk evaluation entails determining probability, severity, and prioritization. Various techniques, including the Delphi Method or expert groups, for estimating probability and severity [8]. Analytical Hierarchy Process (AHP), Data Envelopment Analysis (DEA), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and FMEA for calculating severity weights and priority indices [10]. **For dependent** risks, the Analytic Network Process (ANP) and DEMATEL are preferred [11]. Hybrid models, such as FMEA integrated with AHP, have been reported for calculating severity and prioritizing risks [12]. Similarly, FMEA has been combined with ANP and DEMATEL for enhanced risk analysis [13].

2.4.3 Risk treatment

The risk treatment phase involves selecting and implementing strategies to minimize the likelihood of occurrence and mitigate adverse effects, guided by contingency theory. This phase encompasses preparation, response, and recovery. Strategies include maintaining emergency inventory, fostering cooperation between SC members, enhancing flexibility and resilience, and developing agility to anticipate risks [14].

2.4.4 Risk monitoring

Monitoring requires continuous risk-tracking to evaluate control measures and adjust strategies as needed. Emerging technologies such as the Internet of Things (IoT), blockchain, and Artificial Intelligence (AI) enable real-time risk monitoring [10]. Key areas to assess include suppliers, regulations, and political/economic stability indicators. Predictive analytics and AI techniques to anticipate chain production, transportation, and supply chains risks [11].

2.5 FMEA and DEMATEL in risk management

The FMEA is a systematic method for identifying and assessing product, process, or system failures and developing improvement strategies to eliminate or mitigate them. The process involves identifying potential failures or risks, identifying potential failures or risks, and estimating their probability of occurrence (O), detection (D), and severity (S). By multiplying these factors (OxDxS), the Risk Priority Number (RPN) is calculated.

Many decision-making problems cannot be structured hierarchically due to the interaction and dependency between elements at different levels. The ANP addresses such issues and has been applied in areas such as risk evaluation and supplier selection. However, as noted in [12], ANP can become complex and slow when dealing with multiple elements, potentially leading to confusion. As a result, the DEMATEL method is proposed as a more efficient alternative.

The DEMATEL technique is effective for modeling the influence between components and analyzing cause-and-effect relationships within complex systems. Its advantages have garnered significant attention in the past decade, making it a valuable method for solving complex problems and improving decision-making in various settings [13].
Steps for Applying the DEMATEL Technique according to [15]:

1. Constructing the Influence Matrix

For each expert $x^1, x^2, \dots, x^m$, where m is the number of experts, an influence-relation matrix is developed. The weights provided by all experts are averaged using Equation (1). The final matrix X, as shown in Equation (2), represents the average weights of all experts.

$$\bar{x} = \frac{x^1 + x^2 + \cdots + x^m}{m} \tag{1}$$

$$X = \begin{bmatrix} \bar{x}_{11} & \cdots & \bar{x}_{1j} & \cdots & \bar{x}_{1n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \bar{x}_{i1} & \cdots & \bar{x}_{ij} & \cdots & \bar{x}_{in} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \bar{x}_{n1} & \cdots & \bar{x}_{nj} & \cdots & \bar{x}_{nm} \end{bmatrix}_{nxm} ,i,j\epsilon\{1,\dots,n\} \tag{2}$$

where, $\bar{x}_{ij}$ represents the influence from the *i*-th to the *j*-th attribute. The influence scale consists of five levels: 0 (No influence), 1 (Low influence), 2 (Medium influence), 3 (High influence), and 4 (Very high influence).

2. Calculating the Normalized Influence Matrix

To determine the value of *K*, the maximum sum of rows or columns of *X* is selected, and Equation (3) is applied:

$$K = max_{i,j}\left\{\frac{1}{max_i \sum_{j=1}^{n}|m_{ij}|}, \frac{1}{max_j \sum_{i=1}^{n}|m_{ij}|}\right\} \quad (3)$$

The normalized matrix D is obtained using Equation (4):

$$D = K \times X \quad (4)$$

3. Total Influence Matrix

The total influence matrix *T* is derived using Equation (5), where *I* is the identity matrix.

$$T = \lim_{m\to\infty}(D^1 + D^2 + \cdots + D^m) = D(I - D)^{-1} \quad (5)$$

4. Calculating Cause and Effect Values

The *r* and *c* values are calculated to represent the sum of the row and column values in *T*, respectively, as shown in Equations (6) and (7), the *r* value is considered influence and *c* dependence:

$$r = [r_i]_{n\times1} = \left[\sum_{j=1}^{n} t_{ij}\right]_{n\times1}; i = 1, \dots, n \quad (6)$$

$$c = [c_i]_{1\times n} = \left[\sum_{j=1}^{n} t_{ij}\right]'_{1\times n}; j = 1, \dots, n \quad (7)$$

5. Threshold Value and Visualization

Where *c* is the transpose, subsequently, subsequently, the coordinates are calculated using Equations (8) and (9), and the threshold value α is determined using Equation (10). This threshold represents the average of all elements in the matrix *T*.

The values in cell (*i*, *j*) of matrix *T* that exceed the threshold α indicate that *i* influences *j*; otherwise, no significant influence exists, and these values can be disregarded in the analysis. The interrelation diagram is created by plotting the values of Equation (8) on the *x*-axis and Equation (9) on the *y*-axis. This visualization simplifies causal relationships into a valuable structure for decision-making. The final criteria ranking is obtained by sorting the values from Equations (8) and (9). It is recommended that they be arranged in descending order based on Equation (8) to facilitate interpretation.

$$(r_i + c_j) \quad (8)$$

$$(r_i - c_j) \quad (9)$$

$$\alpha = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} t_{ij}}{N} \quad (10)$$

The coordinate from Equation (8) reflects the degree of importance of a criterion within a set, the higher the value, the greater the importance. On the other hand, Equation (10) represents the relationship of a criterion with others and categorizes them into cause-and-effect groups. A positive value indicates that the criterion is a cause, while a negative value signifies that it is an effect. In Figure 3. The Area I includes causal criteria that require immediate action. Areas II and III group irrelevant criteria, which are independent and have limited influence on the system. Area IV contains problematic criteria that need attention, but not directly, as they represent effect-driven elements.
As reported in [16], a formula is provided to measure the importance of each criterion. Equation (11) calculates the distances, while Equation (12) normalizes the importance. These calculations determine the final weighting Wi of the criteria for the decision-making process.

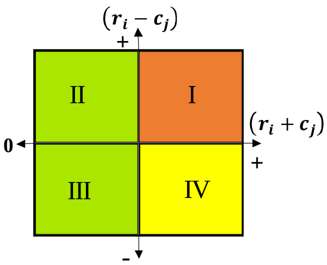

Figure 3 DEMATEL interrelation diagram (based on [17])

$$w_i = \left[(r_i + c_j)^2 + (r_i - c_j)^2\right]^{\frac{1}{2}} \quad (11)$$

$$W_i = \frac{w_i}{max(1\le i\le n, w_i)} \quad (12)$$

The literature highlights various applications of FMEA in combination with DEMATEL: [17] integrated both techniques to identify and prioritize the causes of failures in the photovoltaic cell industry in China. [18] employed them to address the root causes of malfunctions in production lines, enabling faster and more effective problem resolution. [19] applied DEMATEL to evaluate the causal relationships among risk dimensions within the Halal supply chain. In addition, [20] utilized FMEA to assess risks in a machining center and applied DEMATEL to analyze the influences and cause-effect relationships among those risks.

3 Methodology

3.1 Description

The proposed methodology consists of two phases: risk identification and risk evaluation. Figure 4 provides a schematic representation of the process to be followed.

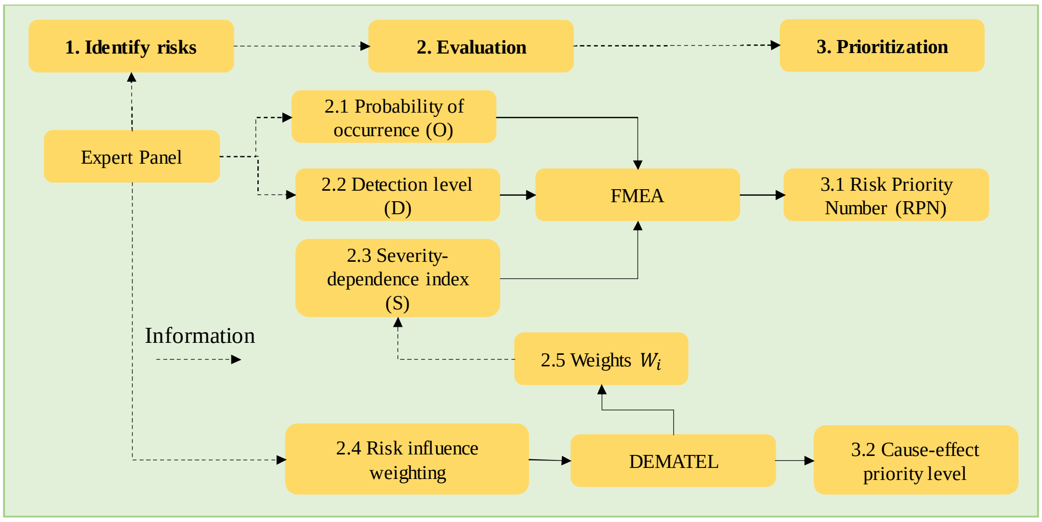

Figure 4 Methodology for the case study

The identification of risks, estimation of the probability of occurrence (O), detection level (D), and weighting of influence are based on the input of eleven experts specializing in the integrated management of Persian lime cultivation. The severity-dependence level (S)-(W_i) is calculated using DEMATEL following Equation (12) referenced in subsection 2.5. Finally, the RPN is determined through FMEA, and the cause-effect relationships among risks are evaluated using DEMATEL.

3.2 Context of the first link in the Persian lime supply chain

The first link in the Agro-Food Supply Chain (AFSC) of Persian lime focuses on its production in orchards, involving small, medium, and large producers. This link determines fruit the fruit volume and quality and synchronizes its flow with the second link, consisting of processing and packing facilities.

The cultivation includes both perennial and seasonal crops, as well as technologically advanced farms with irrigation systems. Persian lime is notable for its larger size, seedlessness, lower acidity, and high vitamin C content. Figure 5 provides a detailed description of the Persian lime cultivation process.

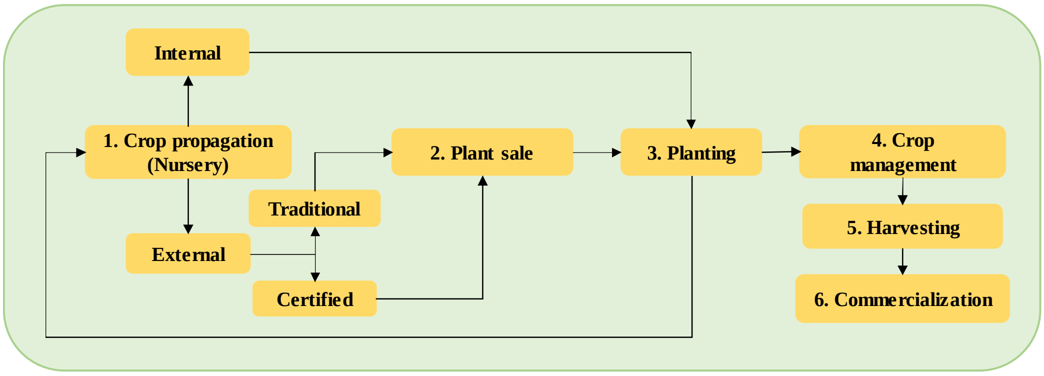

Figure 5 Persian lime cultivation process

The propagation of Persian lime involves activities to reproduce the plant in nurseries. These nurseries can be either internal, owned by producers, or external, focused on production and commercialization. External nurseries can be certified, complying with NOM-079-SAG/FITO-2017, or traditional, which do not follow regulations. Propagation is carried out through grafting onto rootstocks resistant to pests, diseases, and adverse conditions. Once the nursery plant reaches adequate development, it is transplanted into the orchard. Subsequently, integrated crop management is conducted, including pest control, weed management, nutrition, pruning, and irrigation if the necessary technology is available. Harvesting is performed manually by a team of workers, who select the fruit according to the quality standards required by packing facilities. Harvested limes are placed in 25 kg plastic crates, and after collection, they are transported for commercialization.

3.3 Risk identification

In this initial phase, 11 experts in integrated crop management, identified as E1 through E11, were consulted. According to [21], the recommended number of experts ranges from 7 to 30. A total of 53 potential risks were identified through semi-structured interviews. Due to space constraints, all identified risks are included in Annex 1 at the end of the document. Economic thresholds for citrus pests and diseases were established using the strictest averages provided by the experts, which may differ from the existing literature. This study focuses exclusively on pests and diseases posing significant risks to Persian lime cultivation in the Citrus District of Martínez de la Torre, which notably impact production and quality, potentially causing severe disruptions in the SC.

3.4 Risk evaluation

For this step, measurement scales were defined and adapted from [22]. Risk probability was classified as: very high, high, medium, low, and very low, corresponding to occurrences on a weekly, monthly, quarterly, semi-annual, and annual or longer basis, with weights of 9, 7, 5, 3, and 1, respectively. Detection level was stratified as: impossible, low, moderate, high, and specific, with weights of 9, 7, 5, 3, and 1, respectively. These categories range from undetectable to easily detectable without difficulty. Influence was categorized as none, low, moderate, high, and very high, with weights of 0, 1, 2, 3, and 4.

Each expert assessed the probability of occurrence (O) and the detection level (D) for the FMEA technique. The direct influence matrix X was calculated using Equations (1) and (2), the matrix D using (3) and (4), and the total influence matrix T using (5). Calculations were performed using GNU Octave.

Coordinates were derived using Equations (8) and (9), and the threshold value α=0.009 was calculated using Equation (10). All values in matrix T below the threshold were filtered out, resulting in a refined matrix T_2. The final weights W_i for each criterion, representing the **severity level (S)** for FMEA evaluation, were determined using Equation (12). Complete results from FMEA and DEMATEL are provided in Annex 1**.**

4 Results and discussion

The results are divided into two sections: The first one shows findings obtained through the DEMATEL technique, while the second focuses on results from the FMEA analysis.

4.1 Results from DEMATEL

The 53 evaluated risks form a complex network, making a tabular analysis challenging. Therefore, the interrelation diagram described in Section 2.5 was employed. Figure 6 presents this diagram, generated using R Software, illustrating the final influence network as shown below.

$$R33 > R1 > R38 > R6 > R10 > R41 > \cdots > R4 > R27 > R15 > R26 > R21 > R22$$

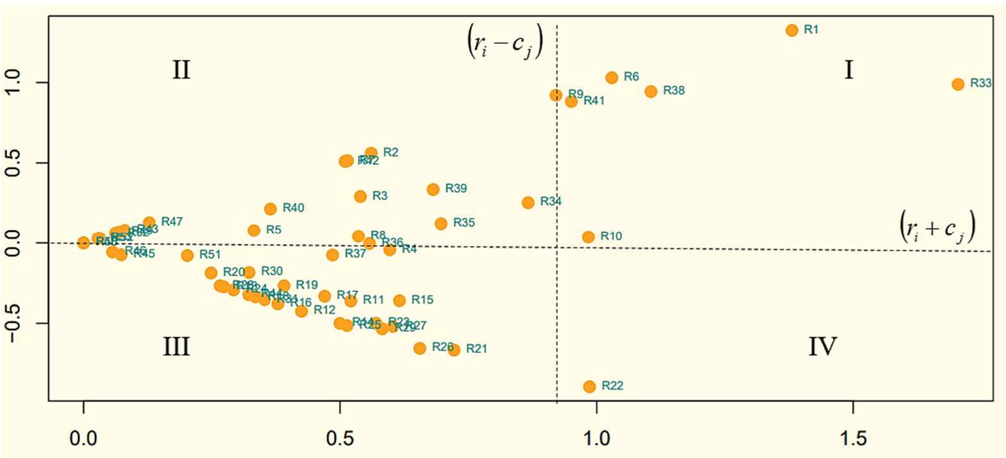

Figure 6 Final cause-and-effect interrelation map

Areas I and II encompass the causal risks that influence others, while Areas III and IV group the effect risks, which are more influenced than they influence.

4.1.1 High-influence causal risks

The most influential causal risks are: R33>R1>R38>R6>R10>R41>R9>R34, most of which are operational in nature. The most significant risk is the "Shortage of pesticides in commercial stores" (R33). Although its probability is low, the impact on crops would be severe, as pests and diseases cannot be controlled without pesticides. This issue primarily affects small, medium, and micro producers who lack the capital for maintaining safety stock. For large producers, this shortage is more associated with financial policies and planning failures, linked to the risk of "Excessive time for resource authorization for purchasing inputs" (R49). The approval process, which may take three to five days, allows pests to proliferate, worsening crop damage.

The second most influential risk is "Hurricane impact" (R1). Hurricanes can cause fruit drop in various growth and flowering stages, uproot trees, damage plants due to wind, and interrupt harvest and commercialization activities. They can also destroy transportation infrastructure and, with heavy rains, increase vulnerability to fungal infections, root rot, and waterlogging damage. The Citric District is highly vulnerable to such events, as seen with hurricanes like Janet (1955), Gilberto (1988), Stan (2005), Karl (2010), and more recently, Grace, which hit near Tecolutla, Veracruz, on August 21, 2021.

Similarly, "High employee turnover" (R38) is related to decreasing workers willing to perform field activities. Low labor supply against high demand drives workers to demand better wages and conditions, leading to short work periods, high turnover, and potential labor disputes. This situation is worsened by absenteeism during local festivals and traditions. Labor is crucial for production, forcing large producers to seek workers from neighboring communities, which raises production costs due to transportation. R38 is linked to other risks such as "Shortage of operational staff" (R34), "Shortage of specialized human resources" (R35), "High labor absenteeism" (R39), and "Operational disruptions due to internal conflicts" (R40).

The warm, humid climate of the Martínez de la Torre Citric District experiences winter temperatures as low as 2°C (December 24, 1989) and spring-summer temperatures reaching up to 43.5°C (April 27, 2011) [23]. This creates risks such as: "High temperatures" (35°C-39°C to >45°C) (R6), "Low temperatures" (<4°C extreme) (R7), "Temperature shifts" (from 22°C-27°C to 28°C-35°C in 1-2 days) (R9), and "Drought (abnormal to extreme)" (R5). Though the region is not officially at risk of extreme drought, [23] reports indicate abnormal to moderate droughts from April to October, occasionally reaching severe to extreme levels. This creates a low likelihood of "Water scarcity or depletion of supply sources" (R8).

The "Impact of a pandemic, epidemic, or seasonal illnesses" (R10) affects the entire supply chain. The COVID-19 health emergency, for instance, negatively impacted the global economy, restricted worker movement, altered demand, and caused production shutdowns. These disruptions in supply chains led to shortages of essential products. It is vital for decision-makers to design contingency plans to increase business resilience, considering other events, such as dengue outbreaks in the warm, humid zone, leading to labor absenteeism. The "Operational disruptions due to external socio-organizational conflicts and/or stakeholders (protests, demonstrations)" (R41) is a low-probability risk, although its frequency is increasing. Protests and road closures due to insecurity and political issues can halt orchard activities for hours or days, delaying scheduled operations.

4.1.2 Low-influence causal risks

Section II of Figure 6 includes low-influence causal risks that affect fewer risks but should still be addressed. These risks are: R35>R39>R2>R3>R8>R7>R42>R40>R5>R47>R43>R49>R32>R52>R53>R48>R50.

Risks like R35, R39, R40, R8, R7 and R5 were previously discussed. The risk of "An earthquake" (R2) has a very low probability, as the region is not in a seismic zone, although seismic waves have been felt. Its including catastrophic effects such as damage to infrastructure and communication routes, injuries, loss of life, operational interruptions, and labor absenteeism.

"Heavy rainfall (>30 mm/h)" (R3) can occur in isolated, atypical events, such as tropical storms, or in severe to extreme conditions, between May and October, particularly from August to October. Intense rains can lead to "Hydrometeorological flooding or hydraulic infrastructure failures" (R4), especially in low areas near rivers or rapid-response streams. The Martínez de la Torre municipality has declared emergency zones on several occasions due to these phenomena. Combined with humidity, these conditions promote the proliferation of pests and diseases in citrus crops.

"Interruption or closure of operations due to non-compliance with regulations" (R42) is a low-probability risk; however, if it occurs, it could severely impact production, resulting in reduced yields and economic losses due to fines. This risk is linked to the lack of permits for operating deep wells and non-compliance with agricultural, labor, and environmental regulations.

"Insufficient processing capacity for integrated pest and disease management" (R47) affects small and medium-sized producers who lack the resources to invest in machinery and tools. This risk is like "Insufficient technological resources for pest and disease monitoring" (R45).

The "Financial impact of crime and insecurity" (R43) manifests as fruit theft and assaults, forcing producers to increase their security expenses. The "Excessive time for financial resource authorization" (R49) mainly affects large producers; bureaucracy can delay the purchase of inputs, exacerbating pest damage. "Acquiring nursery plants carrying diseases" (R32) is a latent risk, especially when buying plants from uncertified nurseries, which can propagate undetectable diseases.

The "Lack of knowledge in integrated crop management" (R53) is common among small producers who rely on inherited practices and lack the resources to hire specialized technicians. This risk relates to "Inadequate nutritional management of the plant" (R52), "Lack of phytosanitary care after pruning" (R48), and "Operational failures in integrated pest management" (R44). The first is critical since a well-nourished plant is more resistant to pests; the second arises from negligence that facilitates the entry of diseases, while the third stems from poor planning and organization.

Finally, "Pesticide restrictions in the market" (R50) is a low-probability but high-impact risk. Restrictions force the use of more expensive, potentially less effective products, which can reduce yields. Continued use of banned or restricted pesticides risks export bans, product rejections, or fines for pesticide residue detection.

4.1.3 Low-effect risks

The risks classified as low effect are: R46>R45>R51>R20>R28>R13>R24>R44>R30>R18>R31>R16>R19>R12>R17>R37>R14>R25>R11>R36>R23>R29>R4>R27>R15>R26>R21. In Quadrant III of Figure 6, these risks mostly involve citrus pests and diseases, influenced by climatic factors and poor crop management.

The group includes "Failures in agricultural machinery and equipment" (R46), an independent event, similar to "Insufficient technological resources for pest and disease monitoring" (R45). However, both can be influenced by other risks, significantly impacting crops. The same applies to "Accidental orchard fire" (R51) and other dangers like R37, R36, R44, and R4.

The topic of citrus pests and diseases is extensive, but only some are briefly described. Most are influenced by natural risks such as hurricanes (R1), heavy rains (R3), floods (R4), high temperatures (R6), low temperatures (R7), abrupt temperature changes (R9), droughts (R5), and water scarcity (R8). For example, "Sectorial streaking" (R28) is associated with heat stress and water shortages, causing chlorotic spots and potentially tree death, with symptoms like "Huanglongbing (HLB)" (R23), complicating diagnosis. Other risks influenced by climatic factors include Green stink bug (R13), Scab (R24), Thrips (R16), Sooty mold or arador (R12), Red spider mite (R14), Melanosis (R25) and White mite (R11).

Among fungal diseases associated with high humidity are: “Dieback” (R27) which causes annual losses of up to 35% of Persian lime trees, reducing production by 60% [24]. It leads to shoot necrosis and defoliation, potentially spreading to roots and killing the plant. “Greasy spot” (R26) primarily affects leaves, causing black spots and premature defoliation, reducing fruit yield by 20% to 45% [25]. “Anthracnose” (R21) leads to flower and fruit drop, resulting in significant production losses.

Some pests promote the development of other diseases. For instance, "Sooty mold" (R29) arises from sugary secretions of pests like the Diaphorina citri (R15), Mealybug (R19), Snow scale (R17) and the Blackfly (R20). Diaphorina citri is also the vector for HLB (R23), a devastating citrus disease that decreases yield and kills trees [25]. This destructive invasive species poses a severe threat to the citrus industry. Another economically impactful disease is the "Citrus tristeza virus" (R31), mainly spread by aphids such as the "brown citrus aphid" (R30).

Lastly, reference must be made to area IV in Figure 6, highlighting high-effect risks that require attention but cannot be improved without addressing their causal risks first. This group includes "Incidence above 5% of trees with Gummosis" (R22), a fungal disease responsible for 10% to 30% of citrus crop losses [26].

4.2 Results obtained with FMEA

The Pareto Law was applied to identify the 20% risks responsible for 80% of the consequences. This grouping, illustrated in Figure 7, includes risks R38, R22, R27, ..., R28, and R18. Full FMEA results can be found in Annex 1 at the end of the document. It is important to note that the FMEA evaluates the Probability of Occurrence (O) and the Detection Level (D), which can result in high RPN. However, it is essential to determine whether the risk is causal or an effect. If a risk is an effect, causal risks must be identified and prioritized for mitigation based on their RPN values. Therefore, priority should be given to addressing all causal dangers first.

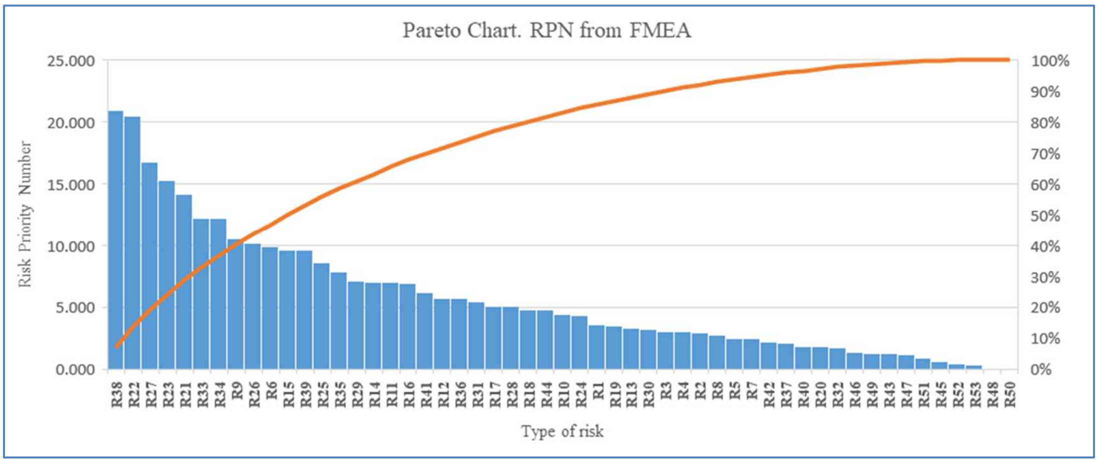

Figure 7 Pareto diagram, results from FMEA

The highest-priority risk identified is “High employee turnover” (R38)**,** followed by “Incidence of more than 5% of trees with Gomosis” (R22). Gomosis, a high-impact risk identified through DEMATEL analysis, is influenced by causal risks such as R1, R3, R4, R5, R6, R7, R9, R17, and R27, which must be addressed first to manage its effects. The third priority is “Dieback” (R27)**,** an effect-driven risk linked to natural causes. Similarly, HLB (R23) is another effect-based risk that requires controlling its vector, Diaphorina citri (R15)**.** “Anthracnose” (R21) is another effect-driven risk caused by natural factors.

Among causal risks within the critical 80%, those requiring priority intervention are: “High employee turnover” (R38), “Scarcity of pesticides in commercial outlets” (R33), “Lack of field workers for diverse tasks” (R34), “Sudden temperature changes” (from 22°C-27°C to 28°C-35°C in 1-2 days) (R9), “High temperatures” (35°C-39°C to >45°C) (R6), “Operational disruptions due to social-organizational conflicts (protests, demonstrations)” (R41). The low-influence causal risks include: “Shortage of specialized human resources” (R35) and the “High absenteeism” (R39), all other risks are effect-based. He least critical risks include R51, R45, R52, R53, R48, and R50.

4.3 Discussion

This study aimed to identify, evaluate, and prioritize risks based on their interdependencies and cause-effect relationships. Data from eleven experts in integrated crop management were processed using DEMATEL for interdependence analysis and FMEA for prioritization. 53 risks were assessed and categorized as natural, pest-related, disease-related, supply-related, and operational risks.

The results were categorized into high- and low-influence causes and low- and high-impact effects. Among the high-influence causes, eight risks were identified, with the scarcity of pesticides in commercial outlets standing out. Although its likelihood of occurrence is low, its realization could significantly impact the crop. Additionally, the effects of hurricanes, high temperatures, and sudden temperature changes directly influence the spread of pests and diseases in citrus crops. Moreover, the pandemic, operational disruptions due to socio-organizational conflicts, workforce shortages, and high employee turnover negatively affect the normal progression of harvest and commercialization activities.

17 risks were classified as low-influence causes, with operational risks predominating, followed by natural-origin risks to a lesser extent. These risks affect a limited number of factors; some are considered independent. Among them are shortages of specialized personnel**,** high employee absenteeism, and seismic events**.** Natural risks, such as intense rainfall**,** water scarcity, and low temperatures, are of particular concern due to their significant impact on the proliferation of pests and diseases.

Effect-group risks are primarily those of natural origin, such as pests and diseases, which are influenced by the causal risks mentioned earlier. A total of 27 low-effect risks were identified, with the most notable being failures in agricultural machinery and equipment**,** insufficient technological resources, and accidental orchard fires. The remainder pertains to citrus pests and diseases. Notably, only one risk is classified as having high influence: a fungal disease known as Gomosis.

Regarding risk prioritization through FMEA, 25 risks account for 80% of the consequences. Among these, six are considered high-influence causes, and two are low-influence causes. These include a high turnover of operational personnel, shortages of pesticides, shortages of operational personnel, abrupt temperature changes, high temperatures, operational interruptions due to external socio-organizational conflicts, shortages,scarcity of specialized human resources, and high labor absenteeism. The remaining 17 risks are effect-based and depend on addressing the causal risks.

Risks with the lowest RPN include a lack of knowledge about integrated crop management**,** insufficient phytosanitary care after tree pruning, and restricting or prohibiting certain pesticides in the target market. This study involved input and evaluations from eleven experts who assessed risks based on defined scales. However, potential individual bias influenced by personal experience or perceptions of risks that do not directly affect them could impact the results. Limited openness to dissent also highlights an area for improvement in the qualitative methodology.

The lack of comprehensive literature on risks in the first stage of the Persian lime supply chain complicates comparisons with previous studies. Nevertheless, this work provides essential literature to support decision-makers in designing risk mitigation strategies. Additionally, it serves as an academic reference for validating results and techniques in future studies, offering a clearer perspective for more effective risk management.

4.4 Conclusions

The results obtained are satisfactory. Experts highlighted notable consistency between the causes and effects of the risksand prioritization based on the likelihood of occurrence and the severity of damage, primarily caused by pests and diseases in crops. Currently, the literature on pest and disease control is fragmented, comprising isolated or outdated studies. Therefore, district. This document should update economic thresholds, present the best treatments and practices, and address the risks associated with the crop.

The Persian lime SC is a crucial economic pillar for the Martínez de la Torre Citrus District, Veracruz, and Mexico. It generates numerous direct and indirect jobs across its links. The production and commercialization of this fruit have significant economic value for producers and intermediaries, with payments made immediately at the time of sale at auction. Furthermore, as a perennial crop, Persian lime allows for near-year-round harvests.

To meet international market demands, the number of planted hectares and packing houses in the region increases annually. In 2020, Mexico ranked as the world's second-largest lime producer, with Martínez de la Torre contributing 31.85% of Veracruz's state production. However, in recent years, the crop has faced a series of natural events related to adverse climatic conditions, pests, diseases, and viruses and operational and supply challenges. Consequently, identifying and assessing these risks is essential to anticipate their effects.

Given the significance of the Persian lime SC, identifying, evaluating, and prioritizing risks in the first link (orchard production) of the supply chain in the Martínez de la Torre Citrus District, Veracruz, Mexico, is of particular interest, as this link ensures supply to the second link (processors and packing houses). The strategy for addressing these risks will depend on individual producers and decision-makers. However, the common goal is to mitigate their impact and reduce their likelihood of occurrence.

This study provides decision-makers with a foundation for designing risk management plans that strengthen the supply chain's resilience. These actions will ensure the continuous food supply and enable processing and packing companies in the second link to meet demand, thereby enhancing the stability and sustainability of the agro-food system against long-term disruptions.

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Review process

Single-blind peer review process.

Annexes

Annex 1 DEMATEL and FMEA evaluation results

Legend: "Type" classifies the risk as 1 = internal and 2 = external. C-E refers to cause-effect: CA = Causal with high influence, CB = Causal with low influence, EB = Low effect, EA = High effect.

S	No	Risk	T	FMEA					DEMATEL			
				P	D	S(*Wi*)	RPN	Rank	ri+ci	ri-ci	Rank	C-E
Natural	R1	Impact of a hurricane.	2	1.000	3.666	0.9711	3.561	29	1.3807	1.3247	2	CA
	R2	Impact of an earthquake.	2	1.000	7.333	0.4023	2.950	35	0.5605	0.5605	11	CB
	R3	Intense rainfall, exceeding 30 mm/h.	2	2.666	3.666	0.3113	3.044	33	0.5396	0.2916	12	CB
	R4	Hydrometeorological flooding or failures in hydraulic infrastructure.	2	2.000	5.000	0.3037	3.037	34	0.5968	-0.0425	48	EB
	R5	Abnormal to extreme drought (lack of rainfall).	2	4.333	3.333	0.1732	2.501	37	0.3320	0.0784	17	CB
	R6	High temperatures, intense heat (35°C-39°C), very high (40°C-44°C) to extreme (45°C or more).	2	4.000	3.333	0.7391	9.854	10	1.0297	1.0297	4	CA
	R7	Low temperatures, moderate (20°C-15°C), strong (14°C-10°C), very strong (9°C-5°C), extreme below to 4°C.	2	2.000	3.333	0.3693	2.462	38	0.5145	0.5145	14	CB
	R8	Water scarcity or depletion of the water supply source	2	3.000	3.333	0.2728	2.728	36	0.5358	0.0423	13	CB

	R9	Temperature changes in a short period, from cool 22°C-27°C to heat 28°C-35°C or more within 1 to 2 days.	2	5.333	3.000	0.6610	10.576	8	0.9209	0.9209	7	CA
	R10	Impact of a pandemic, epidemic, or seasonal diseases (can impact labor shortages, absenteeism, and mobility restrictions).	2	1.666	5.333	0.4998	4.443	27	0.9840	0.0374	5	CA
Pests	R11	Incidence greater than 2u/cm^2 of White mite (*Polyphagotarsonemus latus*)	2	5.000	4.333	0.3216	6.968	17	0.5209	-0.3608	44	EB
	R12	Incidence greater than 3u/cm^2 of Citrus blackfly (*Phyllocoptruta oleivora*)	2	4.333	4.333	0.3049	5.725	20	0.4248	-0.4248	39	EB
	R13	Presence of Citrus green stink bug (*Closterotomus trivialis*)	2	3.333	5.000	0.1961	3.268	31	0.2732	-0.2732	31	EB
	R14	Incidence greater than 3u/cm^2 of Red spider mite on fruit (*Panonychus citri*)	2	5.333	3.666	0.3587	7.014	16	0.4997	-0.4997	42	EB
	R15	Presence of Asian citrus psyllid (*Diaphorina citri Kuwayama*) on new shoots**.**	2	6.666	4.000	0.3618	9.647	11	0.6157	-0.3591	50	EB
	R16	Incidence greater than 1u/cm^2 of Thrips (*Pezothrips kellyanus*)	2	6.333	4.000	0.2718	6.885	18	0.3787	-0.3787	37	EB
	R17	Presence of Snow scale (*Unaspis citri*)	2	4.333	4.000	0.2919	5.059	23	0.4699	-0.3315	40	EB
	R18	The presence of leaf miner (Phyllocnistis citrella) in new shoots.	2	5.000	4.000	0.2404	4.809	25	0.3350	-0.3350	35	EB
	R19	Incidence greater than 2 Mealybugs (*Planococus citri*) per sampled plant.	2	3.333	4.333	0.2400	3.466	30	0.3905	-0.2665	38	EB
	R20	Presence of Citrus blackfly (*Aleurocanthus woglumi*) (Proposed by E5; it affected citrus cultivation in the region in 2004).	2	2.666	4.333	0.1577	1.822	42	0.2485	-0.1865	29	EB
Diseases	R21	Incidence greater than 5% of Anthracnose (*Colletotrichum gloeosporoides*) per sampled tree during flowering.	2	5.666	5.000	0.4986	14.128	5	0.7221	-0.6661	52	EB
	R22	Incidence greater than 5% of trees with Gummosis (*Phytophthora spp.*).	2	5.666	5.333	0.6755	20.416	2	0.9862	-0.8939	53	EA
	R23	Incidence greater than 3% of trees showing visible signs of damage caused by citrus Greening disease (*Huanglongbing*, *Candidatus liberibacter asiaticus*).	2	5.666	7.000	0.3846	15.256	4	0.5698	-0.4996	46	EB
	R24	Incidence greater than 2% of fruits with citrus Scab (*Sphaceloma fawcetti*).	2	3.666	5.666	0.2099	4.361	28	0.2924	-0.2924	32	EB
	R25	Incidence greater than 3% of trees with melanoma (*Diaporthe citri*).	2	3.666	6.333	0.3686	8.559	13	0.5135	-0.5135	43	EB
	R26	Incidence greater than 4% of trees with Greasy spots (*Mycosphaerella citri*).	2	4.333	5.000	0.4704	10.193	9	0.6554	-0.6554	51	EB
	R27	Incidence greater than 2% of the plantation shows visible signs of damage caused by Dieback (*Lasiodiplodia theobromae* and *Fomitopsis meliae*, the causative fungi).	2	5.666	7.333	0.4036	16.774	3	0.6029	-0.5187	49	EB
	R28	Incidence greater than 2% of the plantation showing visible signs of damage caused by Sectorial streak (*wood pocket*).	2	4.666	5.666	0.1911	5.052	24	0.2662	-0.2662	30	EB
	R29	Incidence greater than 3% of fruits per tree with Sooty mold (*Capnodium citri*).	2	3.333	5.333	0.4009	7.127	15	0.5820	-0.5340	47	EB
	R30	Incidence of 2–3 units/cm^2 of the plantation with Brown citrus aphid (*Toxoptera citricida*).	2	4.200	4.000	0.1885	3.167	32	0.3224	-0.1844	34	EB
	R31	Incidence greater than 2% of the plantation showing visible signs of damage caused by citrus Tristeza virus (*Citrus tristeza virus*, severe strain).	2	2.666	8.000	0.2532	5.401	22	0.3527	-0.3527	36	EB
Supply	R32	Acquisition of nursery plants carrying undetectable diseases.	1	5.000	7.666	0.0446	1.708	43	0.0621	0.0621	21	CB
	R33	Shortage of pesticides in commercial stores.	2	3.333	3.666	1.0000	12.222	6	1.7046	0.9881	1	CA
	R34	Shortage of operational staff for various field activities.	2	6.666	4.000	0.4581	12.217	7	0.8666	0.2527	8	CA
	R35	Shortage of specialized human resources (technicians, tractor operators, pruners).	2	4.666	4.666	0.3589	7.817	14	0.6967	0.1214	9	CB
	R36	Shortage of special spare parts for machinery or agricultural equipment.	2	4.666	4.333	0.2828	5.719	21	0.5572	-0.0032	45	EB
	R37	Fuel shortages (diesel or gasoline).	2	2.333	3.666	0.2493	2.133	40	0.4853	-0.0751	41	EB
Operations	R38	High turnover of personnel.	1	5.666	5.000	0.7379	20.907	1	1.1059	0.9437	3	CA
	R39	High absenteeism.	1	5.000	5.000	0.3853	9.632	12	0.6814	0.3346	10	CB
	R40	Operational interruptions due to internal conflicts (work stoppages, strikes, protests, sabotage).	2	2.333	3.666	0.2142	1.832	41	0.3642	0.2132	16	CB

	R41	Operational interruptions due to external socio-organizational conflicts and/or stakeholder actions (protests, demonstrations).	2	2.333	4.000	0.6582	6.143	19	0.9507	0.8821	6	CA
	R42	Operational interruptions or shutdowns due to non-compliance with national and international laws and regulations.	2	2.000	3.000	0.3659	2.195	39	0.5098	0.5098	15	CB
	R43	Negative financial impact due to crime and insecurity (theft, kidnapping, additional security costs, etc.).	2	4.333	5.000	0.0574	1.244	46	0.0800	0.0800	19	CB
	R44	Operational failures in integrated pest and disease management (poor monitoring, delayed interventions, etc.).	1	3.6667	5.666	0.2312	4.804	26	0.3221	-0.3221	33	EB
	R45	Insufficient technological resources are needed to support pest and disease monitoring and prediction, as well as climatic conditions (systems, software, technology).	1	7.000	1.666	0.0527	0.614	49	0.0734	-0.0734	27	EB
	R46	Failures in main agricultural machinery and equipment (tractors, implements, pumps, etc.).	1	6.000	5.666	0.0405	1.376	44	0.0564	-0.0564	26	EB
	R47	Insufficient capacity for integrated pest and disease management (limited resources, conventional machinery, equipment, and tools).	1	5.333	2.333	0.0919	1.143	47	0.1280	0.1280	18	CB
	R48	Lack of phytosanitary attention after tree pruning.	1	5.333	3.333	0.0000	0.000	52	0.0000	0.0000	24	CB
	R49	Excessive time is required for financial resource approval to purchase pesticides and fertilizers (bureaucracy, extensive paperwork, or hierarchy).	1	7.000	3.666	0.0495	1.271	45	0.0690	0.0690	20	CB
	R50	Restriction or prohibition of pesticide molecules in the destination market.	2	2.000	3.000	0.0000	0.000	53	0.0000	0.0000	25	CB
	R51	Accidental orchard fire (due to grassland or sugarcane field burning or drought).	2	1.333	6.000	0.1101	0.881	48	0.2023	-0.0783	28	EB
	R52	Improper nutritional management of plants.	1	3.666	5.666	0.0223	0.462	50	0.0310	0.0310	22	CB
	R53	Lack of knowledge of integrated crop management (control of pests, diseases, and nutrition).	1	4.000	4.333	0.0201	0.348	51	0.0280	0.0280	23	CB