International Journal of Innovative Engineering Applications

Journal homepage: https://dergipark.org.tr/ijiea

RISK ASSESSMENT IN CHEESE PRODUCTION PROCESS USING FAILURE MODE AND EFFECTS ANALYSIS AND INTUITIONISTIC FUZZY TOPSIS

***Ceren Ünlükal*[1], *Mine Şenel*[2*], *Bilgin Şenel*[2], *Kenan Avarbek*[3]**

[1]*Munzur University/Faculty of Engineering/Department of Industrial Engineering, Tunceli, Turkey*
[2]*Muğla Sıtkı Koçman University/Fethiye Faculty of Business Administration/Department of Management Information Systems, Muğla, Turkey*
[3]*Tunceli Mazgirt District Governorship, Social Assistance and Solidarity Foundation Officer, Tunceli, Turkey*

Abstract

Original scientific paper

The aim of this study is to evaluate the cheese production process, which plays a significant role in the milk and dairy industry, in terms of physical, chemical, and microbiological risks using the integrated Failure Mode and Effects Analysis (FMEA) and Intuitionistic Fuzzy TOPSIS (IF-TOPSIS) methods. Although the classical FMEA method is a widely used analytical technique that helps identify and reduce potential risks in processes, it has some drawbacks: such as the possibility that different failure modes may have the same risk priority values (RPN) and risk factor weights. To address this shortcoming, the intuitionistic fuzzy set theory was used to determine the RPN values. This study aimed to identify failures that may occur at critical steps in the production chain, their possible causes, their impact on product quality, and the priority of preventive actions. The study demonstrates that the intuitionistic fuzzy multi-criteria decision-making (MCDM) approach is an effective tool for food safety and quality management in the dairy products industry.

Keywords: *Cheese production, FMEA, food safety, intuitionistic fuzzy TOPSIS (IF-TOPSIS), MCDM, risk analysis.*

PEYNİR ÜRETİM SÜRECİNDE HATA TÜRÜ VE ETKİLERİ ANALİZİ VE SEZGİSEL BULANIK TOPSIS İLE RİSK DEĞERLENDİRMESİ

Özet

Orijinal bilimsel makale

Bu çalışmanın amacı, süt ve süt ürünleri endüstrisinde önemli bir yer tutan peynir üretim sürecinin; fiziksel, kimyasal ve mikrobiyolojik riskler açısından Hata Türü ve Etkileri Analizi (FMEA) ve Sezgisel Bulanık TOPSIS (IF-TOPSIS) yöntemlerinin bütünleşik kullanımıyla değerlendirilmesidir. Klasik FMEA yöntemi süreçlerdeki olası riskleri tanımlamaya ve azaltmaya yardımcı olan ve yaygın olarak kullanılan bir analitik teknik olmasına rağmen, farklı hataların aynı risk öncelik değerlerine ve aynı risk faktörü ağırlığına sahip olabileceği bazı dezavantajlara sahiptir. Bu eksikliği gidermek amacıyla, RÖS (Risk Öncelik Değerleri) değerlerinin belirlenmesinde sezgisel bulanık küme teorisi kullanılmış ve üretim zincirindeki kritik adımlarda ortaya çıkabilecek hatalar, bu hataların olası nedenleri, ürün kalitesine etkileri ve önleyici faaliyetlerin önceliği belirlenmeye çalışılmıştır. Çalışma, süt ürünleri endüstrisinde gıda güvenliği ve kalite yönetiminde sezgisel bulanık çok kriterli karar verme (MCDM) yaklaşımının etkin bir araç olduğunu göstermektedir.

Anahtar Kelimeler: *FMEA, gıda güvenliği, MCDM, peynir üretimi, risk analizi, sezgisel bulanık TOPSIS (IF-TOPSIS).*

1 Introduction

Cheese, one of the oldest fermented foods produced by humankind, is a common name given to a group of milk-based fermented foods produced in a wide variety of flavors and forms all over the world [1,2]. The Turkish Food Codex defines it as "a dairy product obtained by coagulating the raw material using a suitable coagulant and separating the whey from the curd or by coagulating the milk after separating the permeate. It is produced with or without salting by brining or dry salting, with or without starter culture, with or without boiling the curd, with or without flavor, produced according to its technique, consumed before ripening or after ripening, and exhibiting characteristic features specific to its type" [3]. Cheeses can have hundreds of different characteristics depending on their biochemical composition, preparation process, and ripening process - various tastes, textures, smells, shapes, colors, etc. [4].

For cheese production, raw milk collection, addition of coagulating enzymes, curd formation, curd, fresh cheese formation and ripening are among the basic steps involved in cheese making [5,6].

*Corresponding author.
E-mail address: senelmine76@gmail.com (M. Şenel)
Received 17 November 2025; Received in revised form 08 December 2025; Accepted 18 December 2025

Doi: https://doi.org/10.46460/ijiea.1825525

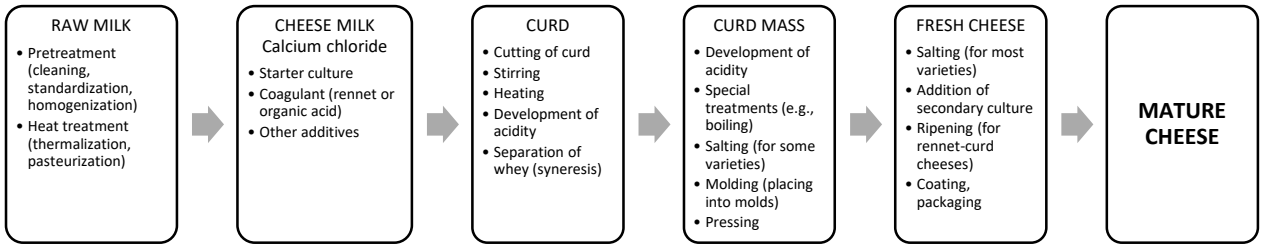

Figure 1. Cheese production process [6].

The milk preparation stage typically involves filtering and, in some instances, gently heating the milk to reach the target temperature. This ensures a clean base and creates optimal conditions for coagulation [7]. Coagulation itself transforms milk into curd through either acidic or enzymatic processes, significantly influencing the curd's texture and characteristics [7,8]. Once coagulated, the curd is carefully cut to release the whey, with the size of the curd particles directly affecting moisture content and texture [9]. Straining, which removes whey during maturation, plays a key role in determining the cheese's composition and ripening process [9,10]. While whey retains soluble components, the majority of casein and fat remains within the curd [10]. The resulting drained curd is then referred to simply as curd. Salting, an essential step for most cheese varieties, can be carried out through dry salting, boiling, brining, or processing with milk, usually using 2-4% NaCl [10,11]. During molding, the curd is placed into molds or manually shaped, providing the final form of the cheese while also facilitating additional whey drainage and structural development [9]. In the ripening phase, cheeses experience microbial, enzymatic, and biochemical transformations-such as lactose fermentation, proteolysis, and lipolysis-that collectively determine their texture and flavor profile [10,12-15].

Cheese inherently resists microbial contamination due to a combination of factors, including its pH, water activity, salt content, presence of nitrites and organic acids, bacteriocin-producing *lactic acid bacteria* (LAB), storage and ripening temperatures, as well as residual enzymatic activity [16-20]. Nevertheless, certain cheese varieties remain highly vulnerable to microbial spoilage. Specifically, physicochemical characteristics such as pH, temperature, protein structure, and fat composition can variably influence both the susceptibility to spoilage and overall cheese safety [18].

Several factors influence the microbial safety and hygienic quality of cheese. These include the origin and microbiological quality of the milk, fat content adjustment, milk homogenization, pasteurization, choice of starter cultures, coagulation, curd formation and mixing, salting, whey removal, milling, molding, and storage conditions. In addition, the hands of production personnel and surfaces that come into contact with cheese have been recognized as potential sources for the transmission of pathogenic microorganisms [21].

The most common hazards encountered in cheese production processes are not only microbiological hazards (*Listeria monocytogenes, Salmonella spp., E. coli O157:H7, Campylobacter jejuni, Staphylococcus aureus*), but also chemical hazards (antibiotic residues) and physical hazards (metal particles or foreign substances) [22].

Therefore, dairy facilities must follow good manufacturing practices and have a food safety plan. An effective method for providing safe cheese to consumers is the implementation of HACCP (Hazard Analysis Critical Control Points) in businesses. The HACCP concept is a systematic approach based on group work that involves identifying and evaluating microbiological, chemical, and physical hazards and risks at all stages of production and distribution, and identifying and controlling damage [22]. The HACCP system has been adopted by national governments over the past few decades and has been implemented internationally to reduce the prevalence of foodborne illness [24,25].

This system is essential for considering and controlling risks that may arise during production processes, preventing contamination, and ensuring food safety. One of the most important steps for this purpose is the identification and analysis of risks inherent in the production process. Therefore, this study analyzes the physical, chemical, and microbiological risks of cheese production stages using Failure Mode and Effects Analysis (FMEA) and Intuitionistic Fuzzy TOPSIS methods, and attempts are made to determine which cheese production stage presents the highest risk.

2 Material and Method

FMEA is a commonly applied analytical approach used to detect, assess, and mitigate both potential and existing failures within a system or process. It supports risk-based decision making by enhancing system reliability and operational safety. Built on the principle of proactively recognizing and resolving problems during the design and production phases, FMEA focuses on uncovering the underlying causes of risk and minimizing their impact, thereby contributing to the consistent delivery of high-quality products and services [26-29].

Food production processes are complex systems where chemical, microbiological, and physical risks are observed simultaneously. Therefore, using only classical numerical methods in the risk assessment process may be insufficient to fully reflect uncertainties. In this context, Intuitionistic Fuzzy Logic-based (IF) approaches offer the advantage of incorporating levels of uncertainty and uncertainty in decision-makers' subjective assessments into the model [30,31].

FMEA is a structured risk assessment method that examines potential failure modes through three key parameters: Occurrence (O), Severity (S), and Detectability (D) [32]. "Occurrence" represents the

likelihood that a failure will take place, whereas "Severity" expresses the extent of harm it may cause to the environment or to customers. "Detectability" refers to the probability of identifying a potential failure before it affects the end user. RPN for each failure mode is calculated by multiplying these three factors. Nevertheless, because traditional FMEA depends heavily on expert judgment, it does not sufficiently capture uncertainty, and failures with identical RPN values cannot be clearly prioritized [33].

To address this limitation, the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method was integrated into FMEA. The TOPSIS method allows each alternative to be ranked according to its distance from the ideal solution [34]. Each failure mode identified in FMEA is treated as an alternative in TOPSIS, and the occurence, severity, and detectability criteria constitute the decision criteria. This allows for a more precise determination of the relative importance of failure modes [35].

Unlike the classical TOPSIS and FMEA approaches, the IF TOPSIS & FMEA method assesses the uncertainty of expert opinions by considering both their membership (μ) and their degree of non-membership (π). Thus, not only their degree of certainty but also their degree of uncertainty is incorporated into the model [36,37]. This method improves decision-making accuracy, especially in systems with high uncertainty, such as food safety [38].

The main advantage of this integration is that it reduces the subjectivity and accuracy limitations of classical FMEA, quantifies uncertainties, and provides decision-makers with a more reliable ranking for prioritizing errors [39,40]. Therefore, prioritizing critical control points in milk and dairy products can be done more accurately.

The process steps of the IF TOPSIS & FMEA model used in failure prioritization are as follows [41]:

Step 1: In the first step of the method, the weights of the experts are determined. If the decision-making group consists of *k* experts, linguistic terms are assigned to evaluate their relative importance, and these linguistic assessments are then converted into the corresponding intuitionistic fuzzy numbers, as presented in Table 1. Let $U_k = \{\mu_k, \nu_k, \pi_k\}$ denote an IF Number (IFN) representing the evaluations of the *k* experts. The expert weights are then computed using the following equations.

Table 1. Linguistic variables and IFN equivalent [41].

Linguistic Variables	IFN Equivalent
Very high	(0.90, 0.10, 0.00)
High	(0.75, 0.20, 0.05)
Average	(0.50, 0.45, 0.05)
Low	(0.35, 0.60, 0.05)
Very low	(0.10, 0.90, 0.00)

$$\lambda_k = \frac{(\mu_k + \pi_k(\frac{\mu_k}{\mu_k + \nu_k}))}{\sum_{k=1}^{n}(\mu_k + \pi_k(\frac{\mu_k}{\mu_k + \nu_k}))} \text{ and } \sum_{k=1}^{n}\lambda_k = 1, k = 1,2,\ldots,n. \quad (1)$$

If it is assumed that all experts have equal importance, use Equation (2):

$$\lambda_k = \frac{1}{n} \text{ and } \sum_{k=1}^{n}\lambda_k = 1, k = 1,2,\ldots,n. \quad (2)$$

Step 2: Based on the evaluations provided by the experts, a combined intuitionistic fuzzy decision matrix is generated. Before the aggregation takes place, an individual decision matrix must be constructed for each expert. This is achieved by assigning linguistic variables defined in Tables 2, 3, and 4. The aggregation of these individual matrices is then performed using the IF Weighted Averaging (IFWA) operator.

Table 2. Linguistic variables and IFN equivalent (Occurrence) [41].

Linguistic Variables	IFN Equivalent
Very high	(0.90, 0.10, 0.00)
High	(0.75, 0.20, 0.05)
Average	(0.50, 0.45, 0.05)
Low	(0.35, 0.60, 0.05)
Very low	(0.10, 0.90, 0.00)

Table 3. Linguistic variables and IFN equivalent (Severity) [41].

Linguistic Variables	IFN Equivalent
Hazardous without warning	(1.00, 0.00, 0.00)
High-risk warnings	(0.90, 0.10, 0.00)
Very much	(0.80, 0.10, 0.10)
Much	(0.70, 0.20, 0.10)
Average	(0.60, 0.30, 0.10)
Low	(0.50, 0.40, 0.10)
Very low	(0.40, 0.50, 0.10)
Inconsiderable	(0.25, 0.60, 0.15)
Very inconsiderable	(0.10, 0.75, 0.15)
None	(0.10, 0.90, 0.00)

Table 4. Linguistic variables and IFN equivalent (Detection) [41].

Linguistic Variables	IFN Equivalent
Absolutely impossible	(1.00, 0.00, 0.00)
Very unlikely	(0.90, 0.10, 0.00)
Unlikely	(0.80, 0.10, 0.10)
Very low	(0.70, 0.20, 0.10)
Low	(0.60, 0.30, 0.10)
Average	(0.50, 0.40, 0.10)
Relatively high	(0.40, 0.50, 0.10)
High	(0.25, 0.60, 0.15)
Very high	(0.10, 0.75, 0.15)
Absolutely possible	(0.10, 0.90, 0.00)

$$\begin{aligned} r_{ij} &= IFWA_\lambda(r_{ij}^{(1)}, r_{ij}^{(2)}, \ldots, r_{ij}^{(l)}) = \lambda_1 r_{ij}^{(1)} \oplus \lambda_2 r_{ij}^{(2)} \oplus \lambda_3 r_{ij}^{(3)} \oplus \ldots \oplus \lambda_l r_{ij}^{(l)} \\ r_{ij} &= [1 - \prod_{k=1}^{l}(1-\mu_{ij}^{(k)})^{\lambda_k}, \prod_{k=1}^{l}(\nu_{ij}^{(k)})^{\lambda_k}, \prod_{k=1}^{l}(1-\mu_{ij}^{(k)})^{\lambda_k} - \prod_{k=1}^{l}(\nu_{ij}^{(k)})^{\lambda_k}] \\ r_{ij} &= \left(\mu_{A_i}(x_j), \nu_{A_i}(x_j), \pi_{A_i}(x_j)\right) \text{and } i = 1,2,3,\ldots,m; j = 1,2,3,\ldots,n. \end{aligned} \quad (3)$$

The aggregated IF decision matrix is constructed as presented below:

$$R = \begin{bmatrix} \mu_{FM_1}(O), \nu_{FM_1}(O), \pi_{FM_1}(O) & \mu_{FM_1}(S), \nu_{FM_1}(S), \pi_{FM_1}(S) & \mu_{FM_1}(D), \nu_{FM_1}(D), \pi_{FM_1}(D) \\ \mu_{FM_2}(O), \nu_{FM_2}(O), \pi_{FM_2}(O) & \mu_{FM_2}(S), \nu_{FM_2}(S), \pi_{FM_2}(S) & \mu_{FM_2}(D), \nu_{FM_2}(D), \pi_{FM_2}(D) \\ \vdots & & \\ \mu_{FM_n}(O), \nu_{FM_n}(O), \pi_{FM_n}(O) & \mu_{FM_n}(S), \nu_{FM_n}(S), \pi_{FM_n}(S) & \mu_{FM_n}(D), \nu_{FM_n}(D), \pi_{FM_n}(D) \end{bmatrix}$$

$$\boldsymbol{R} = \begin{bmatrix} r_{1O} & r_{1S} & r_{1D} \\ r_{2O} & r_{2S} & r_{2D} \\ \vdots & \vdots & \vdots \\ r_{nO} & r_{nS} & r_{nD} \end{bmatrix} \quad (4)$$

Step 3: The risk factors' weights are subsequently defined. Let w_j denote the IFN assigned by expert k to criterion j. Using these evaluations, the criteria's weights are calculated by the IFWA operator, as shown below:

$$w_j = IFWA_\lambda(w_j^{(1)}, w_j^{(2)}, ..., w_j^{(l)}) = \lambda_1 w_j^{(1)} \oplus \lambda_2 w_j^{(2)} \oplus \lambda_3 w_j^{(3)} \oplus ... \oplus \lambda_l w_j^{(l)}$$
$$w_j = [1 - \prod_{k=1}^{l}(1-\mu_j^{(k)})^{\lambda_k}, \prod_{k=1}^{l}(\nu_j^{(k)})^{\lambda_k}, \prod_{k=1}^{l}(1-\mu_j^{(k)})^{\lambda_k} - \prod_{k=1}^{l}(\nu_j^{(k)})^{\lambda_k}] \quad (5)$$

Here $W = [w_1, w_2, w_3, ..., w_j], w_j = [\mu_j, \nu_j, \pi_j], j = 1,2,...,n.$

Step 4: The aggregated weighted IF decision matrix is then established by Equation (6,7,8,9) [30]:

$$R \otimes W = \left\{ \left\langle c, \mu_{FM_i}(x).\mu_w(c), \nu_{FM_i}(c) + \nu_w(c) - \nu_{FM_i}(c).\nu_w(c) \mid c \in X \right\rangle \right\} \quad (6)$$

$$\pi_{FM_iW}(c) = 1 - \mu_{FM_i}(c).\mu_w(c) - \nu_{FM_i}(c) - \nu_w(c) + \nu_{FM_i}(c).\nu_w(c) \quad (7)$$

$$R' = \begin{bmatrix} \mu_{FM_1W}(O), \nu_{FM_1W}(O), \pi_{FM_1W}(O) & \mu_{FM_1W}(S), \nu_{FM_1W}(S), \pi_{FM_1W}(S) & \mu_{FM_1W}(D), \nu_{FM_1W}(D), \pi_{FM_1W}(D) \\ \mu_{FM_2W}(O), \nu_{FM_2W}(O), \pi_{FM_2W}(O) & \mu_{FM_2W}(S), \nu_{FM_2W}(S), \pi_{FM_2W}(S) & \mu_{FM_2W}(D), \nu_{FM_2W}(D), \pi_{FM_2W}(D) \\ \vdots & \vdots & \vdots \\ \mu_{FM_nW}(O), \nu_{FM_nW}(O), \pi_{FM_nW}(O) & \mu_{FM_nW}(S), \nu_{FM_nW}(S), \pi_{FM_nW}(S) & \mu_{FM_nW}(D), \nu_{FM_nW}(D), \pi_{FM_nW}(D) \end{bmatrix} \quad (8)$$

$$R' = \begin{bmatrix} r'_{1O} & r'_{1S} & r'_{1D} \\ r'_{2O} & r'_{2S} & r'_{2D} \\ \vdots & \vdots & \vdots \\ r'_{nO} & r'_{nS} & r'_{nD} \end{bmatrix} \quad (9)$$

Step 5: The positive and negative ideal solution points ($PIS: FM^+$, $NIS: FM^-$) based on IFN are then identified. These ideal solutions are defined using the following equations:

$$\mu_{FM^+W}(c_j) = \left(\left\langle \max_i \mu_{FM^+W}(c_j) \mid j \in J_1 \right\rangle, \left\langle \min_i \mu_{FM^+W}(c_j) \mid j \in J_2 \right\rangle \right) \quad (10)$$

$$\nu_{FM^+W}(c_j) = \left(\left\langle \min_i \nu_{FM^+W}(c_j) \mid j \in J_1 \right\rangle, \left\langle \max_i \nu_{FM^+W}(c_j) \mid j \in J_2 \right\rangle \right) \quad (11)$$

$$\mu_{FM^-W}(c_j) = \left(\left\langle \min_i \mu_{FM^-W}(c_j) \mid j \in J_1 \right\rangle, \left\langle \max_i \mu_{FM^-W}(c_j) \mid j \in J_2 \right\rangle \right) \quad (12)$$

$$\nu_{FM^-W}(c_j) = \left(\left\langle \max_i \nu_{FM^-W}(c_j) \mid j \in J_1 \right\rangle, \left\langle \min_i \nu_{FM^-W}(c_j) \mid j \in J_2 \right\rangle \right) \quad (13)$$

Step 6: The distance measures based on intuitionistic fuzzy sets are then computed. At this stage, the Euclidean distance formula is applied to evaluate how far each alternative is from the ideal solutions. Accordingly, for every alternative, the distances to the IFPIS (S^+) and to the IFNIS (S^-) are calculated as follows:

$$S_i^+ = \sqrt{\frac{1}{2n}\sum_{j=1}^{n}\left[(\mu_{FM_iW}(c_j) - \mu_{FM^+W}(c_j))^2 + (\nu_{FM_iW}(c_j) - \nu_{FM^+W}(c_j))^2 + (\pi_{FM_iW}(c_j) - \pi_{FM^+W}(c_j))^2\right]} \quad (14)$$

$$S_i^- = \sqrt{\frac{1}{2n}\sum_{j=1}^{n}\left[(\mu_{FM_iW}(c_j) - \mu_{FM^-W}(c_j))^2 + (\nu_{FM_iW}(c_j) - \nu_{FM^-W}(c_j))^2 + (\pi_{FM_iW}(c_j) - \pi_{FM^-W}(c_j))^2\right]} \quad (15)$$

Step 7: The relative closeness coefficient (CC_i), which indicates the degree to which each alternative approaches the IFIS, is then calculated for each alternative. The CC_i is obtained using the following expression:

$$CC_i = \frac{S_i^-}{S_i^- + S_i^+} \quad . \quad (16)$$

3 Case Study

This study was conducted in a dairy processing facility located in Tunceli province, with the aim of identifying and prioritizing potential failure modes that may occur during the white cheese production process. The main objective of the study is to quantitatively evaluate the potential physical, chemical, and biological risks that may arise during the production stages of white cheese using IF TOPSIS & FMEA method.

The white cheese production process included in the scope of the analysis consists of the following stages, starting from the acceptance of raw milk to the storage of the final product: (A) Raw milk acceptance, (B) Pasteurization, (C) Cooling to coagulation temperature, (D) Coagulation, (E) Curd maturation, (F) Curd cutting, (G) Curd settling, (H) Pressing, (I) Curd slicing, (J) Brining, (K) Ripening in brine, (L) Packaging in tins, and (M) Storage.

At each stage of process, potential failure modes were classified as physical, chemical, and microbiological risks based on expert opinions. The risk assessment was performed by three experts: the facility owner, the food engineer, and the food technician working in the facility.

Table 5. Failures occurring in processes.

Process	Failure Code	Failure Mode
Raw Milk Acceptance	A1	Microbiological
	A2	Chemical
	A3	Physical
Pasteurization	B4	Microbiological
	B5	Chemical
Cooling to Coagulation Temperature	C6	Microbiological
	C7	Chemical
	C8	Physical
Coagulation	D9	Physical
Curd Maturation	E10	Microbiological
	E11	Physical
Curd Cutting	F12	Microbiological
	F13	Physical
Curd Settling	G14	Microbiological
	G15	Physical
Pressing	H16	Microbiological
	H17	Physical
Curd Slicing	I18	Microbiological
	I19	Physical
Brining	J20	Microbiological
	J21	Physical
Ripening in Brine	K22	Microbiological
Filling into Cans	L23	Microbiological
	L24	Physical
	L25	Chemical
Storage	M26	Microbiological

After identifying the potential failures in each process, the steps are as presented below:

Step 1: Since experts are assumed to be of equal importance, their weights are expressed using Equation (2).

Accordingly, the weight assigned to each expert is represented by $\lambda_k = \frac{1}{3} = 0,33$.

Step 2: The expert evaluations are obtained using the linguistic variables defined in Tables 2, 3, and 4. The individual expert judgments are presented in Table 6.

Experts' evaluations were converted into IFN as shown in Table 7.

The expert evaluations are combined using the IFWA operator.

Table 6. Risk assessment based on expert opinions.

	Expert 1				Expert 2				Expert 3		
	O	**S**	**D**		**O**	**S**	**D**		**O**	**S**	**D**
A1	Average	Very Much	Relatively High	A1	Average	Much	Average	A1	High	Very Much	Relatively High
A2	Average	High-Risk Warnings	Very Low	A2	Average	High-Risk Warnings	Unlikely	A2	Average	Very Much	Very Low
A3	Average	Much	High	A3	Average	Much	Relatively High	A3	Average	Much	High
B4	Average	Very Much	Relatively High	B4	Average	Much	Relatively High	B4	Average	Very Much	Relatively High
B5	Average	Much	Relatively High	B5	Average	Much	Relatively High	B5	Average	Much	Relatively High
C6	Average	Very Much	Relatively High	C6	Average	Much	Relatively High	C6	Average	Very Much	Relatively High
C7	Average	Average	Very High	C7	Average	Average	High	C7	Average	Much	Very High
C8	Average	Much	Relatively High	C8	Average	Much	Relatively High	C8	Average	Much	Relatively High
D9	Average	Average	Very High	D9	Average	Much	Very High	D9	Average	Average	Very High
E10	Average	Very Much	Relatively High	E10	Average	Much	Relatively High	E10	Average	Very Much	Relatively High
E11	Average	Much	Relatively High	E11	Average	Much	Relatively High	E11	Average	Much	Relatively High
F12	Average	Very Much	Relatively High	F12	Average	Much	Relatively High	F12	Average	Very Much	Relatively High
F13	Average	Much	Relatively High	F13	Average	Very Much	Average	F13	Average	Much	Relatively High
G14	Average	Average	Very High	G14	Average	Average	Very High	G14	Average	Average	Very High
G15	Average	Much	Relatively High	G15	Average	Much	Relatively High	G15	Average	Much	Relatively High
H16	Average	Very Much	Relatively High	G16	Average	Very Much	Relatively High	G16	Average	Much	Relatively High
H17	Average	Much	Relatively High	G17	Average	Much	Relatively High	G17	Average	Much	Relatively High
I18	Average	Average	Very High	H18	Average	Average	Very High	H18	Average	Average	Very High
I19	Average	Much	Relatively High	H19	Average	Much	Relatively High	H19	Average	Much	Relatively High
J20	Average	Very Much	Relatively High	I20	Average	Much	Relatively High	I20	Average	Very Much	Average
J21	Average	Average	Very High	I21	Average	Average	Very High	I21	Average	Average	Very High
K22	Average	Very Much	Relatively High	J22	Average	Much	Relatively High	J22	Average	Very Much	Relatively High
L23	Average	Average	Very High	K23	Average	Average	Very High	K23	Average	Average	Very High
L24	Low	Low	High	K24	Low	Low	High	K24	Low	Low	High
L25	Low	Low	Average	K25	Low	Low	Average	K25	Low	Low	Average
M26	Low	Low	Average	L26	Low	Low	Average	L26	Low	Low	Average

Table 7. Decision matrix.

Exp$_1$	***O***	***S***	***D***
A1	(0.50, 0.45, 0.05)	(0.80, 0.10, 0.10)	(0.40, 0.50, 0.10)
A2	(0.50, 0.45, 0.05)	(0.90, 0.10, 0.00)	(0.70, 0.20, 0.10)
A3	(0.50, 0.45, 0.05)	(0.70, 0.20, 0.10)	(0.25, 0.60, 0.15)
B4	(0.50, 0.45, 0.05)	(0.80, 0.10, 0.10)	(0.40, 0.50, 0.10)
B5	(0.50, 0.45, 0.05)	(0.70, 0.20, 0.10)	(0.40, 0.50, 0.10)
C6	(0.50, 0.45, 0.05)	(0.80, 0.10, 0.10)	(0.40, 0.50, 0.10)
C7	(0.50, 0.45, 0.05)	(0.60, 0.30, 0.10)	(0.10, 0.75, 0.15)
C8	(0.50, 0.45, 0.05)	(0.70, 0.20, 0.10)	(0.40, 0.50, 0.10)
D9	(0.50, 0.45, 0.05)	(0.60, 0.30, 0.10)	(0.10, 0.75, 0.15)
E10	(0.50, 0.45, 0.05)	(0.80, 0.10, 0.10)	(0.40, 0.50, 0.10)
E11	(0.50, 0.45, 0.05)	(0.70, 0.20, 0.10)	(0.40, 0.50, 0.10)
F12	(0.50, 0.45, 0.05)	(0.80, 0.10, 0.10)	(0.40, 0.50, 0.10)
F13	(0.50, 0.45, 0.05)	(0.70, 0.20, 0.10)	(0.40, 0.50, 0.10)
G14	(0.50, 0.45, 0.05)	(0.60, 0.30, 0.10)	(0.10, 0.75, 0.15)
G15	(0.50, 0.45, 0.05)	(0.70, 0.20, 0.10)	(0.40, 0.50, 0.10)
H16	(0.50, 0.45, 0.05)	(0.80, 0.10, 0.10)	(0.40, 0.50, 0.10)
H17	(0.50, 0.45, 0.05)	(0.70, 0.20, 0.10)	(0.40, 0.50, 0.10)
I18	(0.50, 0.45, 0.05)	(0.60, 0.30, 0.10)	(0.10, 0.75, 0.15)
I19	(0.50, 0.45, 0.05)	(0.70, 0.20, 0.10)	(0.40, 0.50, 0.10)
J20	(0.50, 0.45, 0.05)	(0.80, 0.10, 0.10)	(0.40, 0.50, 0.10)
J21	(0.50, 0.45, 0.05)	(0.60, 0.30, 0.10)	(0.10, 0.75, 0.15)
K22	(0.50, 0.45, 0.05)	(0.80, 0.10, 0.10)	(0.40, 0.50, 0.10)
L23	(0.50, 0.45, 0.05)	(0.60, 0.30, 0.10)	(0.10, 0.75, 0.15)
L24	(0.35, 0.60, 0.05)	(0.50, 0.40, 0.10)	(0.25, 0.60, 0.15)
L25	(0.35, 0.60, 0.05)	(0.50, 0.40, 0.10)	(0.50, 0.40, 0.10)
M26	(0.35, 0.60, 0.05)	(0.50, 0.40, 0.10)	(0.50, 0.40, 0.10)
Exp$_2$	***O***	***S***	***D***
A1	(0.50, 0.45, 0.05)	(0.70, 0.20, 0.10)	(0.50, 0.40, 0.10)
A2	(0.50, 0.45, 0.05)	(0.90, 0.10, 0.00)	(0.80, 0.10, 0.10)
A3	(0.50, 0.45, 0.05)	(0.70, 0.20, 0.10)	(0.40, 0.50, 0.10)
B4	(0.50, 0.45, 0.05)	(0.70, 0.20, 0.10)	(0.40, 0.50, 0.10)
B5	(0.50, 0.45, 0.05)	(0.70, 0.20, 0.10)	(0.40, 0.50, 0.10)
C6	(0.50, 0.45, 0.05)	(0.70, 0.20, 0.10)	(0.40, 0.50, 0.10)
C7	(0.50, 0.45, 0.05)	(0.60, 0.30, 0.10)	(0.25, 0.60, 0.15)
C8	(0.50, 0.45, 0.05)	(0.70, 0.20, 0.10)	(0.40, 0.50, 0.10)
D9	(0.50, 0.45, 0.05)	(0.70, 0.20, 0.10)	(0.10, 0.75, 0.15)
E10	(0.50, 0.45, 0.05)	(0.70, 0.20, 0.10)	(0.40, 0.50, 0.10)
E11	(0.50, 0.45, 0.05)	(0.70, 0.20, 0.10)	(0.40, 0.50, 0.10)
F12	(0.50, 0.45, 0.05)	(0.70, 0.20, 0.10)	(0.40, 0.50, 0.10)
F13	(0.50, 0.45, 0.05)	(0.80, 0.10, 0.10)	(0.50, 0.40, 0.10)
G14	(0.50, 0.45, 0.05)	(0.60, 0.30, 0.10)	(0.10, 0.75, 0.15)
G15	(0.50, 0.45, 0.05)	(0.70, 0.20, 0.10)	(0.40, 0.50, 0.10)
H16	(0.50, 0.45, 0.05)	(0.80, 0.10, 0.10)	(0.40, 0.50, 0.10)
H17	(0.50, 0.45, 0.05)	(0.70, 0.20, 0.10)	(0.40, 0.50, 0.10)
I18	(0.50, 0.45, 0.05)	(0.60, 0.30, 0.10)	(0.10, 0.75, 0.15)
I19	(0.50, 0.45, 0.05)	(0.70, 0.20, 0.10)	(0.40, 0.50, 0.10)
J20	(0.50, 0.45, 0.05)	(0.70, 0.20, 0.10)	(0.40, 0.50, 0.10)
J21	(0.50, 0.45, 0.05)	(0.60, 0.30, 0.10)	(0.10, 0.75, 0.15)
K22	(0.50, 0.45, 0.05)	(0.70, 0.20, 0.10)	(0.40, 0.50, 0.10)
L23	(0.50, 0.45, 0.05)	(0.60, 0.30, 0.10)	(0.10, 0.75, 0.15)
L24	(0.35, 0.60, 0.05)	(0.50, 0.40, 0.10)	(0.25, 0.60, 0.15)
L25	(0.35, 0.60, 0.05)	(0.50, 0.40, 0.10)	(0.50, 0.40, 0.10)
M26	(0.35, 0.60, 0.05)	(0.50, 0.40, 0.10)	(0.50, 0.40, 0.10)

Table 7 (Continued). Decision matrix.

Exp_3	*O*	*S*	*D*
A1	(0.75, 0.20, 0.05)	(0.80, 0.10, 0.10)	(0.40, 0.50, 0.10)
A2	(0.50, 0.45, 0.05)	(0.80, 0.10, 0.10)	(0.70, 0.20, 0.10)
A3	(0.50, 0.45, 0.05)	(0.70, 0.20, 0.10)	(0.25, 0.60, 0.15)
B4	(0.50, 0.45, 0.05)	(0.80, 0.10, 0.10)	(0.40, 0.50, 0.10)
B5	(0.50, 0.45, 0.05)	(0.70, 0.20, 0.10)	(0.40, 0.50, 0.10)
C6	(0.50, 0.45, 0.05)	(0.80, 0.10, 0.10)	(0.40, 0.50, 0.10)
C7	(0.50, 0.45, 0.05)	(0.70, 0.20, 0.10)	(0.10, 0.75, 0.15)
C8	(0.50, 0.45, 0.05)	(0.70, 0.20, 0.10)	(0.40, 0.50, 0.10)
D9	(0.50, 0.45, 0.05)	(0.60, 0.30, 0.10)	(0.10, 0.75, 0.15)
E10	(0.50, 0.45, 0.05)	(0.80, 0.10, 0.10)	(0.40, 0.50, 0.10)
E11	(0.50, 0.45, 0.05)	(0.70, 0.20, 0.10)	(0.40, 0.50, 0.10)
F12	(0.50, 0.45, 0.05)	(0.80, 0.10, 0.10)	(0.40, 0.50, 0.10)
F13	(0.50, 0.45, 0.05)	(0.70, 0.20, 0.10)	(0.40, 0.50, 0.10)
G14	(0.50, 0.45, 0.05)	(0.60, 0.30, 0.10)	(0.10, 0.75, 0.15)
G15	(0.50, 0.45, 0.05)	(0.70, 0.20, 0.10)	(0.40, 0.50, 0.10)
H16	(0.50, 0.45, 0.05)	(0.70, 0.20, 0.10)	(0.40, 0.50, 0.10)
H17	(0.50, 0.45, 0.05)	(0.70, 0.20, 0.10)	(0.40, 0.50, 0.10)
I18	(0.50, 0.45, 0.05)	(0.60, 0.30, 0.10)	(0.10, 0.75, 0.15)
I19	(0.50, 0.45, 0.05)	(0.70, 0.20, 0.10)	(0.40, 0.50, 0.10)
J20	(0.50, 0.45, 0.05)	(0.80, 0.10, 0.10)	(0.50, 0.40, 0.10)
J21	(0.50, 0.45, 0.05)	(0.60, 0.30, 0.10)	(0.10, 0.75, 0.15)
K22	(0.50, 0.45, 0.05)	(0.80, 0.10, 0.10)	(0.40, 0.50, 0.10)
L23	(0.50, 0.45, 0.05)	(0.60, 0.30, 0.10)	(0.10, 0.75, 0.15)
L24	(0.35, 0.60, 0.05)	(0.50, 0.40, 0.10)	(0.25, 0.60, 0.15)
L25	(0.35, 0.60, 0.05)	(0.50, 0.40, 0.10)	(0.50, 0.40, 0.10)
M26	(0.35, 0.60, 0.05)	(0.50, 0.40, 0.10)	(0.50, 0.40, 0.10)

Table 8. Aggregated decision matrix.

	O	*S*	*D*
A1	(0.603, 0.343, 0.053)	(0.771, 0.126, 0.103)	(0.435, 0.464, 0.100)
A2	(0.500, 0.450, 0.050)	(0.874, 0.100, 0.026)	(0.738, 0.159, 0.103)
A3	(0.500, 0.450, 0.050)	(0.700, 0.200, 0.100)	(0.304, 0.565, 0.132)
B4	(0.500, 0.450, 0.050)	(0.771, 0.126, 0.103)	(0.400, 0.500, 0.100)
B5	(0.500, 0.450, 0.050)	(0.700, 0.200, 0.100)	(0.400, 0.500, 0.100)
C6	(0.500, 0.450, 0.050)	(0.771, 0.126, 0.103)	(0.400, 0.500, 0.100)
C7	(0.500, 0.450, 0.050)	(0.637, 0.262, 0.101)	(0.153, 0.696, 0.151)
C8	(0.500, 0.450, 0.050)	(0.700, 0.200, 0.100)	(0.400, 0.500, 0.100)
D9	(0.500, 0.450, 0.050)	(0.637, 0.262, 0.101)	(0.100, 0.750, 0.150)
E10	(0.500, 0.450, 0.050)	(0.771, 0.126, 0.103)	(0.400, 0.500, 0.100)
E11	(0.500, 0.450, 0.050)	(0.700, 0.200, 0.100)	(0.400, 0.500, 0.100)
F12	(0.500,0.450,0.050)	(0.771, 0.126, 0.103)	(0.400, 0.500, 0.100)
F13	(0.500,0.450,0.050)	(0.738, 0.159, 0.103)	(0.435, 0.464, 0.100)
G14	(0.500,0.450,0.050)	(0.600, 0.300, 0.100)	(0.100, 0.750, 0.150)
G15	(0.500,0.450,0.050)	(0.700, 0.200, 0.100)	(0.400, 0.500, 0.100)
H16	(0.500,0.450,0.050)	(0.771, 0.126, 0.103)	(0.400, 0.500, 0.100)
H17	(0.500,0.450,0.050)	(0.700, 0.200, 0.100)	(0.400, 0.500, 0.100)
I18	(0.500,0.450,0.050)	(0.600, 0.300, 0.100)	(0.100, 0.750, 0.150)
I19	(0.500,0.450,0.050)	(0.700, 0.200, 0.100)	(0.400, 0.500, 0.100)
J20	(0.500,0.450,0.050)	(0.771, 0.126, 0.103)	(0.435, 0.464, 0.100)
J21	(0.500,0.450,0.050)	(0.600, 0.300, 0.100)	(0.100, 0.750, 0.150)
K22	(0.500,0.450,0.050)	(0.771, 0.126, 0.1039	(0.400, 0.500, 0.100)
L23	(0.500,0.450,0.050)	(0.600, 0.300, 0.100)	(0.100, 0.750, 0.150)
L24	(0.350,0.600,0.050)	(0.500, 0.400, 0.100)	(0.250, 0.600, 0.150)
L25	(0.350,0.600,0.050)	(0.500, 0.400, 0.100)	(0.500, 0.400, 0.100)
M26	(0.350,0.600,0.050)	(0.500, 0.400, 0.100)	(0.500, 0.400, 0.100)

Since the factors are not weighted in the study, the process proceeds to the next steps.

Step 5: IFPIS and IFNIS are identified according to the IFN.

Table 9. IFPIS and IFNIS.

	O	*S*	*D*
FM^+	(0.50, 0.45, 0.05)	(0.874, 0.10, 0.026)	(0.738, 0.159, 0.103)
FM^-	(0.35, 0.60, 0.05)	(0.50, 0.40, 0.10)	(0.100, 0.750, 0.150)

Step 6: Distance measures are calculated based on IF sets.
Step 7: CC_i for the IF ideal solution is computed separately for each alternative.

Table 10. Distance measures and closeness coefficients.

	S_i^+	S_i^-	CC_i	Ranking
A1	0.193	0.281	0.593	2
A2	0.000	0.416	1.000	1
A3	0.258	0.183	0.415	7
B4	0.203	0.241	0.543	5
B5	0.215	0.216	0.502	6
C6	0.203	0.241	0.543	5
C7	0.347	0.121	0.259	9
C8	0.215	0.216	0.502	6
D9	0.376	0.117	0.238	10
E10	0.203	0.241	0.543	5
E11	0.215	0.216	0.502	6
F12	0.203	0.241	0.543	5
F13	0.188	0.244	0.564	4
G14	0.383	0.104	0.214	11
G15	0.215	0.216	0.502	6
H16	0.203	0.241	0.543	5
H17	0.215	0.216	0.502	6
I18	0.383	0.104	0.214	11
I19	0.215	0.216	0.502	6
J20	0.183	0.255	0.582	3
J21	0.383	0.104	0.214	11
K22	0.203	0.241	0.543	5
L23	0.383	0.104	0.214	11
L24	0.345	0.087	0.201	12
L25	0.257	0.218	0.459	8
M26	0.257	0.218	0.459	8

Table 11. Total closeness coefficients of the processes.

Process	Total CC_i	Ranking
A	2.008	1
B	1.044	4
C	1.303	2
D	0.238	10
E	1.044	4
F	1.107	3
G	0.715	7
H	1.044	4
I	0.715	7
J	0.795	6
K	0.543	8
L	0.874	5
M	0.459	9

4 Results and Discussion

In this study, potential failure types that may arise during the white cheese production process were examined using the Intuitionistic Fuzzy TOPSIS & FMEA approach. Through the analysis, S_i^+, S_i^- and CC_i were computed for the failure modes associated with each process stage.

According to the results obtained, the highest risk priority value is for A2 (chemical failure mode, CC_i = 1.000), followed by A1 (microbiological failure mode, CC_i = 0.593), J20 (biological failure mode, CC_i = 0.582), and F13 (physical failure mode, CC_i = 0.564).

As a result of the analysis, the total risk scores for the process steps in cheese production were also calculated. According to the analysis, the highest risk value of 2.008 was observed in the "Raw Milk Acceptance" process. This indicates that the quality of raw materials in milk and dairy production directly affects product safety and quality. Since raw milk represents the starting point of the production chain, it is the stage where microbiological, chemical, and physical contamination risks are most pronounced [42,43]. Therefore, preventive controls such as temperature monitoring, microbiological testing, and chemical residue analyses must be meticulously conducted during raw milk acceptance.

The second-highest risk is observed in the "Cooling to Coagulation Temperature" process (C, 1.303), followed by the "Curd Cutting" process (F, 1.107) in third place. These two stages are critical points where the structural characteristics and final quality of the cheese are determined. Temperature deviations during cooling can lead to bacterial imbalances and texture problems, while the curd cutting stage carries risks of equipment-related physical contamination or mechanical deformation [44]. Therefore, process standardization, equipment hygiene, and the implementation of automated temperature monitoring systems are recommended at these stages.

Among the processes in the medium-risk group are "Brining" (J, 0.795), "Filling into Cans" (L, 0.874), and "Pasteurization" (B, 1.044). In particular, insufficient control of temperature and time parameters during pasteurization poses risks for both product safety and nutritional value [45]. In the brining and filling into cans processes, microbial risks associated with hygiene conditions are more prominent. Therefore, the implementation of automated salt concentration monitoring systems and personnel hygiene training is recommended at these stages.

Although "Storage" (M, 0.459), "Curd Maturation" (E, 1.044), and "Pressing" (H, 1.044) processes have relatively lower risk scores, the possibility of secondary contamination still exists. In particular, temperature, humidity, and shelf-life conditions during storage should be continuously monitored.

5 Conclusion

The safety of food stands as the element in the manufacture of milk and dairy items directly affecting the well-being of consumers. Elements including raw material quality, regulation of temperature, avoidance of cross-contamination and cleanliness of equipment are

essential to ensuring safety throughout each phase of the production process particularly for products like cheese that are highly susceptible, to microbial contamination.

In this study the FMEA and Intuitionistic Fuzzy TOPSIS approaches aimed to identify the steps within the cheese manufacturing process where food safety hazards are most prevalent. The results show that improvements in raw milk acceptance, Cooling-Coagulation Temperature and Curd Cutting phases are essential for minimizing risks. Generally the research results indicate that the greatest dangers, in the cheese production process occur in the early stage of production and the risk level gradually decreases as the process progresses. This indicates that risk management strategies in the dairy sector ought to embrace a method concentrating mainly on raw inputs and early processing phases [46,47]. In this respect, the implementation of the integrated approach used in the study together with food safety management systems such as HACCP and ISO 22000 in food production facilities will contribute to more accurate determination of process risks and more reliable prioritization of critical control points, thus improving food safety performance.

In conclusion, the IF-TOPSIS & FMEA method has been demonstrated to be an effective, systematic, and applicable tool for assessing the multidimensional and uncertain nature of risks in cheese production processes. In future studies, combining real-time sensor data, machine learning-based predictive models, or digital twin applications with this approach offers significant opportunities for achieving more dynamic and predictive food safety management in the milk and dairy products sector.

6 Declarations

6.1 Conflict of Interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

6.2 Funding

No funding was received for this work.

6.3 Authors' Contribution

C.Ü-Conceptualization, Formal Analysis, Writing-Original Draft, Methodology. M.Ş-Conceptualization Formal Analysis, Writing-Original Draft, Writing Review and Editing. B.Ş-Conceptualization, Formal Analysis, Writing-Original Draft, Writing Review and Editing. K.A-Data Collection. All authors read and approved the final submitted version of this manuscript.

6.4 Acknowledgment

We would like to express our gratitude to the cheese production facility staff and management who provided support in the field implementation of this study, data collection stages, and evaluation of the technical details of the production process.

6.5 Data Availability Statement

All data that supports the findings of this study are included within the article

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