

Optimizing Food Traceability Technologies in Manufacturing Industries: A Multi-Criteria Decision Analysis Using TOPSIS

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Abstract

As food safety concerns continue to escalate, robust food traceability systems have become a critical necessity in the food manufacturing industry. A comprehensive analysis of novel technologies and traceability techniques has been presented in this study. These technologies and approaches include Radio Frequency Identification (RFID), barcode technology, blockchain, Internet of Things (IoT), DNA barcoding and enterprise resource planning (ERP). The research aims to determine which of these novel technologies offers the ideal solution for effective food traceability technology by using the TOPSIS approach. The analysis encompasses a comprehensive examination of the primary factors such as cost, accuracy, compatibility, reliability, scalability, data security & privacy, and user-friendliness affecting technology selection, accompanied by weighted allocations for each aspect. Emphasising the critical role of Food Traceability Systems (FTS) in averting recent outbreaks, the study also integrates insights from expert opinion interviews along with comprehensive surveys, involving eleven experts with diverse professional backgrounds and experience levels ranging from 1 to 18 years, including roles such as quality control, factory and production management. Findings from this study underscore the importance of balancing technological efficiency with industry-specific practicalities. While barcode technology remains dominant, achieving a performance score of 0.699, IoT closely followed barcode technology with a performance score of 0.523, while blockchain DNA Barcoding, ERP, and RFID 0.448, 0.386, 0.368, and 0.306 followed respectively, each presenting unique trade-offs requiring strategic managerial consideration. This research provides valuable insights for food manufacturers seeking to optimize their traceability strategies and ensure compliance with evolving food safety regulations however future advancements in AI and machine learning-driven traceability systems may shift industry preferences.

Keywords

Food Traceability, Food Safety, TOPSIS, Decision Making, Food Manufacturing Industry.

Introduction

The importance of food traceability has escalated in recent years due to concerns about food safety. Food traceability alludes to the capability to monitor food items across the entire food chain, spanning from pro-

cessing to distribution. The ISO 22005 Food Safety Standard requires every business in the food chain to be aware of its suppliers and customers and mandates the utilization of designated codes and fundamental standards for creating and executing food and feed traceability systems (Urbano et al., 2020). This includes the identification of information such as the food's origin, processing parameters, time and date of production, as well as other information pertaining to food safety and the responsible organisation. Tracing can occur at various stages of the product lifecycle and includes both forward and backward tracing of food products. Forward tracing refers to recording and

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tracking product data from farm to table. Similarly, backward tracing involves accessing and reviewing the product's history from fork to farm, or from the consumer back to the farm. Olsen and Borit (2013) defined traceability as "The ability to access any or all information relating to that which is under consideration, throughout its entire life cycle, by means of recorded identifications". Furthermore, food traceability is the capability to trace the origin of a food product throughout its journey, understanding its entire history from farm to logistics, warehousing, production, delivery and retail of processed foods (Regattieri, Gamberi & Manzini, 2007; Olsen & Aschan, 2010). By providing consumers with access to a wealth of data about the origin and processing of their food, traceability systems foster trust and brand loyalty (Wang et al., 2017).

Today's quality assurance systems must encompass food quality, safety, environmental impact and clear traceability from farm to table, reflecting the demands of consumers and the entire food chain (Opara & Mazaud, 2001). It is particularly critical in complex, multi-tiered supply chains where transparency is often limited (Tse & Tan, 2012). The recent foodborne recalls reported by public health agencies such as the Centers for Disease Control and Prevention (CDC) are evidence that the need for a proper traceability system is still essential for effective recalling and preventing food safety issues. Proper recalling of food products is also important to satisfy customer demands (CDS, 2026; Chen, 2014).

Food Standards Agency (FSA) reported a decline in food recalls across England, Wales and Northern Ireland throughout 2024/25. This improvement is attributed to several factors, including the adoption of advanced technologies to reduce risks and enhancements in production processes. However, challenges remain, and continued efforts are needed to ensure food safety and quality. Developing robust technologies within the food supply chain is essential for effective traceability and efficient product recalls, helping address safety concerns and minimise future recalls (FSA, 2025).

Numerous advanced technologies have been developed in recent years by software organisations. However, selection of the technology from the bulk is not an easy task considering all the factors that a food manufacturing industry generally needs. Despite the abundance of available technologies, there is no proper latest definitive research ranking the most effective technology, particularly when considering all the criteria food industries must consider. Poor technology choices can compromise operational performance, resulting in financial losses for the organisations (Jadhav & Sonar, 2009). Furthermore, ensuring transparency within food chains through the adoption of technol-

ogy requires significant commitment from all parties involved. This entails addressing various obstacles and requirements, including technical considerations such as network connectivity, data storage requirements, security of the device and compliance with the government laws, as well as concerns related to consumer acceptance (Astill et al., 2019). Moreover, to achieve efficient traceability, it is imperative to conduct thorough research for a better understanding of technologies and to select the most suitable ones. The selection process involves careful consideration of several factors, which are critical to the success of the project.

To achieve this, this study will utilise TOPSIS for decision-making which evaluate the options according to various criteria and rank them accordingly. This approach incorporates the weightage of relative criteria according to the expert's opinions and literature review. To this end, this study has evaluated various technologies and sought expert opinions and identified the optimal technology for food traceability. The opinions of experts were obtained from a diverse group, including factory managers, process owners, quality managers, production managers, software engineers and MBA students who provided valuable insights from their respective fields of expertise.

The research holds relevance for food manufacturing industries and emerging businesses that may have overlooked the intricacies of food traceability. This study is poised to aid such industries in technology selection, optimization of existing technology and the enhancement of their food safety protocols. By utilising the TOPSIS methodology, the research leverages comprehensive attribute information, assigns numerical rankings to alternatives and addresses interdependencies among attribute preferences (Behzadian et al., 2012). Ultimately, the aim is to pinpoint the most suitable solution among the available technology alternatives. TOPSIS was selected for this analysis due to its ability to handle multi-criteria decision problems in a structured and computationally efficient manner, particularly when comparing a finite set of alternatives based on their relative distance to an ideal solution. Furthermore, prior studies have demonstrated its suitability for manufacturing and process selection problems; for instance, Ghaleb et al. (2020) found TOPSIS to be more appropriate for manufacturing process selection in terms of agility when compared with other MCDM techniques. Additionally, given that various MCDM methods differ in their approaches to weighting, uncertainty handling, and computational complexity (Bączkiewicz, 2021; Taherdoost, 2023), TOPSIS offers a balanced approach that is both transparent and practical for decision-making in complex industrial contexts such as food traceability systems.

The article is structured as follows: the next section offers the literature review that comprehensively examines existing research, identifying gaps that this study aims to address. Next, it delves into the methodology employed for analysis and calculations, elucidating the approach taken to derive results. The culmination of the analysis is presented in results section, which unveils the final solutions and outcomes. In the discussion section, it critically evaluates the results in light of the literature review, highlighting their significance and implications. Finally, the last section serves as the conclusion, summarizing key insights gleaned from the study and delineating avenues for future research.

Literature review

The modern food processing has many complexities, characterized by intricate global supply chains and diverse ingredients, necessitating the capture and analysis of vast quantities of data (Haleem, Khan & Khan, 2019). Traditional methods of tracking food products in the supply chain using paper-based documentation, laboratory-based detection of adulterants and contaminants, and manual data entry are struggling to keep up with the complexities of modern food systems. According to Costa et al. (2013) and Violino et al. (2019), such traditional approaches are inadequate for certain products and regarded as expensive, laborious and they require sophisticated equipment. To address these issues, it is imperative to integrate technology into food traceability systems (Galimberti et al., 2019). Moreover, the integration of current technologies and computational models further enhances the value of traceability systems by fostering communication between stakeholders and providing standardised frameworks for operational efficiency, managing food crises, preserving product quality and identity, preventing fraud and food wastage, ensuring food safety, building consumer confidence and promoting quality throughout the food supply chain. (Dabbene, Gay & Tortia, 2014; Badia-Melis, Mishra & Ruiz-Garcia, 2015; Wang, Yue & Zhou, 2017). Advancements in information technology have positioned traceability as a cornerstone of modern food safety practices, offering clear and verifiable information from producers to consumers (Badia-Melis, Mishra & Ruiz-Garcia, 2015; Wang, Yue & Zhou, 2017). However, challenges remain ensuring interoperability, standardization and efficient data exchange across complex supply chains (Scholten et al., 2016).

The industry demands readily applicable and affordable traceability techniques that can be seamlessly integrated into existing operations. Barcode and RFID

are the identification technologies that have brought a notable change in food traceability. These technologies have made it easier to identify products and batches swiftly and precisely (Luvisi et al., 2012; Yang et al., 2016; Qian et al., 2022). RFID improves the effectiveness of the supply chain by retaining crucial data like production site, cultivation methods, manufacturing processes and other details that customers consider essential when making purchases (Zhang & Li, 2012; Badia-Melis, Mishra & Ruiz-Garcia, 2015). Despite being recognised as an advanced technology ensuring the reliability and traceability of the supply chain, the expense of RFID tags remains a significant challenge, albeit prices have dropped considerably in recent years (Aarnisalo et al., 2007; Aung & Chang, 2014). While RFID technology has the potential to facilitate tracking and tracing of each product, the associated costs may be prohibitive, particularly for a vast array of prepackaged food products (Li et al., 2017). Nevertheless, RFID technology promises enhanced reliability and efficiency for food traceability systems due to its superior reading rate compared to traditional barcodes (Hong et al., 2011; Badia-Melis, Mishra & Ruiz-Garcia, 2015).

As for Barcode, they play a crucial role in enabling inventory tracking in real-time, effectively mitigating the risks associated with overstocking or understocking, thereby ensuring product freshness and availability together with Quick Response (QR) codes (Tarjan et al., 2014). With their advantageous combination of high capacity and low cost, QR codes are particularly well-suited for identifying small wheat flour packages, chosen for their compact size, rapid scanning speed and ability to accommodate extensive information compared to other 2D barcode alternatives (Qian et al., 2012). In contrast to one-dimensional counterparts, two-dimensional (2D) barcodes excel in information storage capacity by employing a matrix of dots and spaces, a characteristic that has contributed to their widespread adoption in retail over the past three decades (Ghaani et al., 2016; Qian et al., 2021).

DNA barcoding serves as a sophisticated technology in food traceability, entailing the sequencing of a regularized genetic region for species recognition (Galimberti et al., 2019; Mampang et al., 2023). This is a reliable method for validating the authenticity of food products and ensuring adherence to labelling regulations, thereby strengthening traceability within the food industry. DNA barcoding also plays a pivotal role in tracing seafood and FISH-BOL (Fish Barcode of Life), certifying the quality and provenance of raw materials and identifying contaminations along the food supply continuum. Particularly in scenarios involving intricate manufacturing processes or fragmented fish products where traditional identification

methods falter, DNA barcoding emerges as an invaluable asset (Galimberti et al., 2013). Unlike conventional methods, DNA barcoding allows for the simultaneous identification of multiple species without necessitating an in-depth understanding of individual genome sequences, making it an efficient and dependable approach (Fanelli et al., 2021). However, while advanced methods like chemometrics and DNA barcoding offer unparalleled efficiency in traceability, their implementation may not always be the most cost-effective solution for food manufacturers (Badia-Melis, Mishra & Ruiz-Garcia, 2015).

ERP systems are instrumental in enhancing food traceability by amalgamating diverse business processes and furnishing a centralized platform for data management, thereby facilitating efficient supply chain management and real-time information dissemination across organizational departments (Harvey, 2024). Vanany et al. (2019) have devised an open ERP system tailored for halal meat processing, offering a cost-effective alternative for small and medium processing industries compared to professional ERP systems. The customized software within this open-source ERP system streamlines processes, enabling swift identification of non-“halalness” in raw materials through automatic error notifications. However, adaptability remains a challenge, necessitating adjustments to align with specific business processes and regulations in each case study (Vanany et al., 2019). Yuan, Yeh & Lu (2011) have developed a tracing module for ERP systems, highlighting the extensive data preparation required from various sources such as bill of materials, suppliers, purchasing information and shop floor operations. ERP-integrated traceability systems offer the advantage of seamless integration between functions, facilitating easy data exchange. While ERP systems have demonstrated their efficacy in providing solutions for numerous companies, the implementation costs remain a significant concern, requiring substantial investments of both time and resources (Ali & Miller, 2017; Vanany et al., 2019).

Technologies like blockchain and Big Data analytics, play crucial roles in managing and utilising data across food supply chains. Blockchain promises to have a significant impact on data transparency, enabling comprehensive data capture from the starting point to consumption, leading to improved food labelling and consumer education (Liivat, 2025). Nevertheless, challenges arise concerning decentralization versus ensuring privacy in food traceability, particularly regarding concerns about data confidentiality and the consensus mechanisms like proof of work (PoW) and proof of stake (PoS) that involve nodes to compete for digital resources and wealth to verify transactions,

thus posing obstacles to scalability and stability in blockchain-IoT systems for food traceability (Tsang et al., 2019). IoT serves as the central technology facilitating data acquisition from various stages within supply chains, ultimately fostering transparent food production systems (Astill et al., 2019). As IoT techniques advance, there is a growing emphasis on strategies that enable increased autonomy among interconnected entities (Chen, 2015). The autonomous system for the identification and traceability difficulties in the food chain utilising the latest technologies like IoT and RFID was discussed in the paper on developing an autonomous tracing system (Chen, 2015). Additionally, blockchain technology, as implemented by major retailers like Walmart and Kroger, has further transformed traceability by allowing for rapid determination of product origins and movement paths. The ability to minimise product recalls, a primary indicator of a traceability system’s effectiveness, is another significant benefit facilitated by these advancements (Qian et al., 2022). In Tab. 1, describes how each technology plays a role in food traceability.

Choosing the appropriate traceability technology is a challenging and intricate endeavor due to the involvement of numerous factors and criteria (Khan et al., 2018). When determining the most efficient FT (Food Traceability) Technology for a business, cost, accuracy, compatibility, reliability, scalability, data security and privacy, and user-friendliness were considered with the help of expert’s opinions as these are pivotal in deciding a suitable traceability technology for Food Supply Chains (FSC) (Khan et al., 2018). These factors are shown in the Table 2.

The perceived benefits of implementing traceability technologies must be carefully weighed against the associated costs including initial implementation, maintenance, training, upgrade, and total cost of ownership (Kelepouris, Pramataris & Doukidis, 2007). By prioritizing cost in the selection and implementation of traceable technologies, businesses can better leverage their potential benefits while mitigating financial constraints. Accuracy refers to how closely a measured value matches the true value, holds significant importance (Astill et al., 2019). In the food production, precision of results, consistency of performance, and decreased error rates help empower food manufacturers to gather increasingly precise data throughout the production process (Fan, 2014; Ruiz-Garcia & Lunadei, 2010; Islam, Manning & Cullen, 2021). Compatibility refers to the level at which developers perceive a methodology to harmonize with their existing practices. This includes incorporation with existing systems, interoperability with other systems, and cross-platform compatibility. The reliability factor

Table 1
Comparison of each Technology

Technology	Factors	Role in traceability	Reference
RFID	Readability, High data storage capacity, Speed.	Able to identify the existence of tagged products using radio waves, relying solely on the reader for data collection.	Tarjan et al., 2014; Hong et al., 2011; Qian et al., 2012; Ruiz-Garcia & Lunadei, 2010
Blockchain	Scalability, Data handling, Reliability, Data security, Fraud-resistant.	Guarantees the secure collection of data and monitoring livestock products in real-time within the supply chain, ensuring data integrity and preventing tampering.	Feng Tian, 2017; Tsang et al., 2019; Patel et al., 2023
IoT	Scalability, Compatibility, Flexibility.	Capable of identifying, tracing and recording data across the entirety of the supply chain.	Tan & Sidhu, 2022
Barcode	Speed, Reliability, Readability, High data storage capacity.	Enables product identification and supports efficient data collection across the supply chain.	Tarjan et al., 2014; Qian et al., 2012
DNABarcoding	Accuracy, Reliability, Capability, Low cost.	Able to detect adulteration, spoilage, allergenic species in such as in seafood, FISH- BOL and other complex food matrices.	Galimberti et al., 2019; Mampang et al., 2023
ERP	High cost, Reliability, Accuracy.	Centralized data management system. It needs data collection technologies.	Harvey, 2024; Vanany et al., 2019

including system uptime, fault tolerance, and error handling, along with data accuracy, plays an effective role in the selection of appropriate traceability tools decision (Regattieri, Gamberi & Manzini, 2007). Scalability, which refers to the capability to adjust to the environmental changes and fulfil future needs, is a critical aspect emphasized by Gupta, Christie & Manjula (2017). The scalability, in this context comprises of the ability to handle increased workload, performance under high demand, and horizontal and vertical scalability. The integration of digital technologies in modern supply chains enhances product traceability, data sharing and visibility, but also increases the likelihood of cyber threats, such as data breaches, operational disruptions and reputational and financial harm (Syed et al., 2022). Encryption mechanisms, access control measures, compliance with regulations, and data anonymization techniques are therefore play a pivotal role in data security and privacy of traceability systems (Ahmed, 2023). The implementation of traceability technology relies heavily on its user-friendliness where user interface, ease of navigation, customization options, and availability of user support and documentation are of great importance (Manos & Manikas, 2010; Kittipanya-Ngam & Tan, 2020; Mattevi & Jones, 2016; Razak, Hendry, & Stevenson, 2023). System providers are encouraged to conduct activities aimed at enhancing users' comprehension of the benefits offered by the traceability system, as greater understanding increases the likelihood of sustained usage (Tseng et al., 2022). Furthermore, all stakehold-

ers should encourage the development of traceability tools and user-friendly data processing software to foster further advancements in this field (Bosona & Gebresenbet, 2013).

In conclusion, the literature review conducted in this study provides literature on existing research regarding various food traceability technologies as well as various factors while deciding a suitable traceability technology in food manufacturing.

Materials & Methods

After the identification of technologies including IoT, Blockchain, barcode, DNA Barcoding, RFID and Enterprise Resource Planning (ERP), the factors were determined with the help of experts. The experts possess diverse experiences and designations, which are detailed below in Table 3. Their participation is needed to, determine and assess criteria and prioritize alternatives according to those criteria. The experts were selected using purposive sampling based on their relevant experience and expertise in the food technology and food industry. Specifically, individuals holding key operational and managerial roles such as quality control, factory and production management, process ownership, and product management were identified to ensure informed contributions to the study.

After this, the performance matrix is formed. This involves ranking the relevance of each criterion to every alternative. To evaluate the alternatives in terms

Table 2
Comparison of Factors

Acronym	Factors	Description
CT	Cost	Initial implementation cost
		Maintenance cost
		Training cost
		Upgrade cost
		Total cost of ownership (TCO)
AC	Accuracy	Precision of results
		Consistency of performance
		Error rate
CO	Compatibility	Incorporation with existing systems
		Interoperability with other systems
		Cross-platform compatibility
RE	Reliability	System uptime
		Fault tolerance
		Error handling
SC	Scalability	Ability to handle increased workload
		Performance under high demand
		Horizontal and vertical scalability
DSP	Data Security and Privacy	Encryption mechanisms
		Access control measures
		Compliance with regulations.
		Data anonymization techniques
UF	User-friendliness	User interface
		Ease of navigation
		Customization options
		Availability of user support and documentation

of criteria, a 5-point scale is used. This scale helps in rating the performance of each alternative against the given criteria, with 5 being the highest and 1 being the lowest score. Later, Multi-Criteria Decision Making Method (MCDM) has been chosen for evaluation, with the TOPSIS approach being utilised for analysis. Real-world problems often involve multiple conflicting criteria, making it challenging to find a solution that satisfies all of them simultaneously (Opricovic & Tzeng, 2004). TOPSIS is an MCDM, which was proposed by Hwang & Yoon (Opricovic & Tzeng, 2004). The principle of this approach is that the optimal al-

Table 3
Experts' designation and experience

Experts	Designation	Experience (Years)
Exp-1	Quality Control	3
Exp-2	Manager Quality	18
Exp-3	Factory Manager	2
Exp-4	Factory Manager	3
Exp-5	Factory Manager	14
Exp-6	Manager	10
Exp-7	Process owner	12
Exp-8	Production Manager	6
Exp-9	Director Product Management	16
Exp-10	MBA Student	1
Exp-11	Software Engineer	8

ternative should be distant from the negative ideal solution and close to the positive ideal solution. If the criterion is cost, the effective solution will be totally opposite (Opricovic & Tzeng, 2004). Liang et al. (2023) noted that, when compared to other options, sometimes the solution closest to the ideal outcome in terms of Euclidean distance might also be the closest to the anti-ideal outcome.

The process of analyzing and selecting the technologies is inherently challenging due to uncertainty surrounding technology production, including the ambiguity of expert assessments, the multifaceted nature of technologies and interconnections among technologies (Halicka, 2020). To aid in technology selection, both qualitative and quantitative methods can be applied (Halicka, 2020). Among these methods, AHP and TOPSIS are commonly utilized for technology selection (Halicka, 2020). Halicka (2020) specifically mentioned using TOPSIS for selecting road technologies and criteria.

Yurdakul and Iç (2005) benefitted from TOPSIS to create a performance measurement model for manufacturing industries. Chu (2002) employed Fuzzy TOPSIS for plant location selection and Huang (2008) used TOPSIS for information system selection. Monjezi et al. (2012) employed TOPSIS to investigate blasting operations in a limestone mine and select the most appropriate blasting pattern. İc (2012) incorporated TOPSIS into their analysis for selecting computer-integrated manufacturing (CIM) Technologies. Additionally, TOPSIS has been widely applied across various aspects of the food industry by different authors. Ardakani, Bartolini & Brunori (2017) used TOPSIS to develop a dynamic national-level food and nutrition

security index for Iran, prioritizing vulnerabilities in the food system. [Ortiz-Barrios et al. \(2019\)](#) employed TOPSIS to discern high- performance pork suppliers from low-performance ones. [Ocampo \(2019\)](#) combined TOPSIS with a fuzzy analytic hierarchy process to rank sustainability- enhancing practices in food manufacturing firms. [Lukic, Kljenak & Anddelić \(2020\)](#) investigated the performance in finance of food retailers in Serbia using TOPSIS alongside AHP. [Selim, Yunusoglu & Yilmaz Balaman \(2016\)](#) used fuzzy TOPSIS to prioritize tasks of maintenance for machines in an international food company. [Hajiaghahi-Keshmeli et al. \(2023\)](#) employed Pythagorean Fuzzy TOPSIS to select green suppliers in the food sector. Additionally, [Khosravi et al. \(2011\)](#) utilized TOPSIS to choose an appropriate milling system for rice based on multiple criteria, while [Wang and Ji \(2014\)](#) assessed food safety in supermarkets with the same method. Finally, these studies collectively demonstrate the versatility of TOPSIS in addressing diverse challenges within the food industry, from quality evaluation and supplier selection to sustainability assessment and system optimization. The algorithm of TOPSIS comprises of several steps and were taken throughout this analysis ([Taherdoost & Madanchian, 2023](#)).

Step 1: The first step is to establish a performance matrix; this matrix is formed by taking expert opinions through surveys. All the questions regarding the alternatives and criteria and how each key criterion plays a role in each question are formed. It is the criterion. The equation below (1) is the performance matrix $\mathbf{X}$.

$$\mathbf{X} = \begin{bmatrix} x_{11} & \dots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \dots & x_{mn} \end{bmatrix}_{m \times n} \quad (1)$$

Step 2: The normalization of the matrix is the second step. This is done to normalize the matrix which is in different scales. The equation below (2) is used to normalize each x_{ij} of the matrix. Here $i = 1, \dots, m$ and $j = 1, \dots, n$.

$$q_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^m x_{ij}^2}} \quad (2)$$

In the normalized matrix, the criteria weights are also included $W = \{w_1, \dots, w_n\}$. The weights should satisfy the below equation (3).

$$\sum_{j=1}^n w_j = 1 \quad (3)$$

Step 3: In order to form weighted normalized matrix, each criteria weight is multiplied with the respective column of the normalized matrix

$$V_{ij} = w_j q_{ij} \quad (4)$$

Step 4: The positive ideal solution V^+ and negative ideal solution V^- is calculated by the following equation. Positive solution is the performance which is best and negative solution is the performance which is worst of the alternatives. where J is associated with the benefit criteria and J' is associated with the cost criteria (5) and (6).

$$V^+ = \{v_1^+, v_2^+, \dots, v_n^+\} \\ = \left\{ \left(\max_i v_{ij} \mid j \in J \right), \left(\min_i v_{ij} \mid j \in J' \right) \right\} \quad (5)$$

$$V^- = \{v_1^-, v_2^-, \dots, v_n^-\} \\ = \left\{ \left(\min_i v_{ij} \mid j \in J \right), \left(\max_i v_{ij} \mid j \in J' \right) \right\} \quad (6)$$

Step 5: The separation measure is the distance of alternatives with V^{+*} and V^- are calculated. The Euclidean Distance formula is used for this and is mentioned below (7 & 8).

$$D_i^+ = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^+)^2} \quad (7)$$

$$D_i^- = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^-)^2} \quad (8)$$

Step 6: Relative closeness is calculated using the below formula (9).

$$C_i^* = \frac{D_i^-}{D_i^+ + D_i^-} \quad (9)$$

Step 7: According to descending value of C_i^* , ranking is done. In general, the selection should be the alternative with the highest value of the relative closeness.

Results

The TOPSIS analysis requires knowledge of the weightage of each criterion to form the normalized matrix. The process commences with soliciting expert opinions, during which participants were requested to assess the criteria based on their significance in food traceability systems. The ranking is utilized to weigh the criteria and participants were asked to respond

through a survey, ranking the criteria on a scale of 1–5. It is important to note that the exact weightage values need not be weighed, but experts' opinions regarding the criteria's importance are critical in the ranking process. Before forming the normalised matrix (Table 5), the performance matrix (Table 4) is formed. This matrix is taken from the responses of participants who ranked the criteria's role in each alternative. The criteria are ranked against each alternative based on the criterion's significance in each alternative. Presented below as Table 4, this matrix delineates the performance of each technology, denoted as alternatives, based on the ranked criteria.

Table 4
Performance Matrix

Technology/ Criterion	CT	AC	CO	SC	RE	DSP	UF
RFID	3.91	4.55	3.8	4.09	4.18	3.91	3.91
BAR	4.18	4.36	4.55	4.45	4.64	4.18	4.91
DNA	4.2	4.7	4.1	4	4.5	4.4	3.9
BLOCK	4.45	4.55	4.2	4.36	4.45	4.7	3.91
ERP	4.45	4.36	4.27	4.55	4.27	4.09	4
IOT	4.64	4.55	4.36	4.55	4.36	4.18	4.55

Table 5
Normalized Matrix

Technology/ Criterion	CT	AC	CO	SC	RE	DSP	UF
RFID	0.769	0.874	0.755	0.802	0.813	0.774	0.779
BAR	0.822	0.837	0.904	0.872	0.903	0.828	0.978
DNA	0.826	0.903	0.815	0.784	0.875	0.872	0.777
BLOCK	0.875	0.874	0.835	0.855	0.86	0.931	0.779
ERP	0.875	0.837	0.849	0.892	0.831	0.810	0.797
IOT	0.912	0.874	0.867	0.892	0.848	0.828	0.906

To ensure uniformity across all metrics, it is imperative to normalize the performance matrix presented above. This normalization process entails dividing every value by the square root of each criterion's cumulative sum of values.

To determine the optimal technology, it is crucial to rank the technologies relative to the significance of the factors required for effective implementation in traceability technology. To gauge the significance levels of these criteria, experts were solicited to rank their importance on a scale ranging from 1 to 5. The ensuing Table 6 and 7 present the rankings provided by eleven experts regarding the significance of criteria within traceability technology. This comprehensive

assessment offers invaluable insights into the prioritization of criteria, thereby facilitating informed decision-making in selecting the most suitable technology.

Table 6
Criteria Ranking

Expert	CT	AC	CO	SC	RE	DSP	UF
Exp-1	1	1	1	2	1	1	1
Exp-2	3	4	5	3	4	5	4
Exp-3	3	4	3	5	5	4	4
Exp-4	4	5	5	4	5	4	4
Exp-5	3	5	5	5	5	5	5
Exp-6	4	2	4	4	5	4	5
Exp-7	5	4	4	5	4	5	5
Exp-8	5	5	5	5	5	5	5
Exp-9	5	5	3	4	5	2	4
Exp-10	5	4	4	5	5	3	4
Exp-11	5	5	5	5	5	5	5

Utilizing the rankings provided by the eleven experts to prioritize the criteria, the average scale was computed. Subsequently, the weightage of each criterion was determined by dividing each average scale rating by the sum of all the criteria average ratings. These weights, depicted in the rightmost column of Table 7, are integral components in calculating the weighted normalized matrix which is in Table 8 below. This calculation involves multiplying the weightage of each criterion by its respective value in the normalized matrix (Table 5) and denoted as v_{ij} , thereby facilitating a comprehensive assessment of the comparative relevance of each criterion in the framework of decision-making.

In Table 9, the optimal and least favorable values for each criterion are identified. It is essential to note that a high rank in every criterion does not necessarily signify the best value. For instance, in the context provided, the cost criterion is non-beneficial; a higher cost is invariably disadvantageous for companies. Therefore, the best value for cost corresponds to the minimum value. In contrast, the remaining criteria are deemed advantageous, thus the highest value signifies the optimal outcome. Conversely, for non-beneficial criteria which is cost, the worst value is the highest, while for beneficial criteria, it is the lowest. In technical terms, the optimal and least favorable values are denoted as the positive ideal solution (V^+) and the negative ideal solution (V^-), respectively.

The calculation of the distance from the ideal solutions is conducted for each technology, as outlined in Table 10. This involves determining the distance from V^+ , represented as D^+ and the distance from V^- , de-

Table 7
Criteria Ranking with Details

Criterion	1	2	3	4	5	Average	Weight
CT	EXP-1		EXP-2, EXP-3, EXP-5	EXP-4, EXP-6	EXP-7, EXP-8, EXP-9, EXP-10, EXP-11	3.9	0.135
AC	EXP-1		EXP-6	EXP-2, EXP-3, EXP-7, EXP-10	EXP-4, EXP-5, EXP-8, EXP-9, EXP-11	4.09	0.1419
CO	EXP-1		EXP-3, EXP-9	EXP-6, EXP-7, EXP-10	EXP-2, EXP-4, EXP-5, EXP-8, EXP-11	4	0.1388
SC		EXP-1	EXP-2	EXP-4, EXP-6, EXP-9	EXP-3, EXP-5, EXP-7, EXP-8, EXP-10, EXP-11	4.27	0.1482
RE	EXP-1			EXP-2, EXP-7	EXP-3, EXP-4, EXP-5, EXP-6, EXP-8, EXP-9, EXP-10, EXP-11	4.45	0.1545
DSP	EXP-1	EXP-9	EXP-10	EXP-3, EXP-4, EXP-6	EXP-2, EXP-5, EXP-7, EXP-8, EXP-11	3.9	0.1356
UF	EXP-1			EXP-2, EXP-3, EXP-4, EXP-9, EXP-10	EXP-5, EXP-6, EXP-7, EXP-8, EXP-11	4.18	0.1451

noted as D^- . And v_{ij} is from the weighted normalised matrix. These distances are computed using the Euclidean distance formula, as specified in equations (7) and (8) provided subsequently.

The performance score indicates that BAR and IOT have the highest score whereas RFID has the lowest score in which Barcode has the highest performance score of 0.69935 and Radio Frequency Identification has the lowest performance score of 0.306274. Based on the performance scores mentioned above, the definitive ranking of the food traceability technologies is established in Table 12.

The analysis was carried out using Microsoft Excel, which was employed for organising the data, per-

forming the TOPSIS calculations, and ranking the alternatives based on the computed relative closeness. Excel was chosen due to its flexibility, transparency, and ease of handling multi-criteria decision-making computations. To ensure the validity and reliability of the results, a validation procedure was implemented through cross-verification of all computational steps, including the normalisation of the decision matrix, application of criterion weights, determination of positive ideal and negative-ideal solutions, and calculation of distance from ideal solutions. Additionally, intermediate and results were reviewed to ensure consistency and accuracy in the ranking outcomes, thereby minimising the risk of computational or input errors.

Table 8
Weighted Normalised Matrix

<i>Technology/Factor</i>	CT	AC	CO	SC	RE	DSP	UF
RFID	0.104	0.124	0.105	0.1188	0.1256	0.105	0.113
BAR	0.111	0.119	0.1256	0.1293	0.1395	0.112	0.141
DNA	0.111	0.128	0.1131	0.1162	0.1353	0.1182	0.112
BLOCK	0.118	0.124	0.1159	0.1267	0.1338	0.1263	0.113
ERP	0.118	0.119	0.1178	0.1322	0.1284	0.1099	0.115
IOT	0.123	0.124	0.1203	0.1322	0.1311	0.1123	0.131

Table 9
Positive and Negative Ideal Solutions

Criteria	CT	AC	CO	SC	RE	DSP	UF
V+	0.1038	0.1281	0.1256	0.1322	0.1395	0.1263	0.1419
V-	0.1232	0.1189	0.1049	0.1162	0.1256	0.1050	0.1127

Table 10
Distance from Ideal Solution

Technology	Positive Ideal solution D_i^+	Negative Ideal Solution D_i^-
RFID	0.045851	0.020243
BAR	0.01847	0.042965
DNA	0.037481	0.023604
BLOCK	0.034858	0.028292
ERP	0.0379	0.022101
IOT	0.028192	0.030929

Table 11
Performance Score

<i>Technology</i>	C_i^*
RFID	0.306274
BAR	0.69935
DNA	0.386412
BLOCK	0.448013
ERP	0.36834
IOT	0.523146

Discussion

The comparative analysis of traceability technologies based on the literature review and empirical evaluation reveals both alignment and discrepancies across

Table 12
Food Traceability Technologies Ranking

Acronym	Technology	Rank
RFID	Radio Frequency Identification	6
BAR	Barcode technology	1
DNA	DNA Barcoding	4
BLOCK	Blockchain	3
ERP	Enterprise Resource Planning	5
IOT	Internet of Things	2

key performance criteria. Beginning with RFID, the empirical analysis confirmed its strengths in accuracy (4.6 out of 5), reliability (4.18 out of 5), and scalability (4.09 out of 5). However, a notable divergence emerged regarding cost perceptions. Contrary to literature highlighting high implementation costs, the empirical findings suggest a more moderate perception of cost (3.9 out of 5), positioning it as the lowest-cost option among the evaluated technologies. Additionally, despite RFID's established accuracy benefits, the analysis identified limitations in compatibility (3.8 out of 5), user-friendliness, data security, and privacy (each rated at 3.91 out of 5), indicating areas requiring managerial attention for effective deployment.

Barcode technology demonstrated high congruence with literature findings, excelling in user-friendliness (4.91 out of 5), reliability (4.65 out of 5), compatibility (4.55 out of 5), and scalability (4.45 out of 5). However, both empirical results and literature underscored concerns in data security and privacy (4.18 out of 5), highlighting potential vulnerabilities that managers must consider in decision-making processes.

For DNA barcoding, the empirical results corroborated its high accuracy (4.7 out of 5) and reliability (4.5 out of 5), along with low cost (4.2 out of 5), aligning closely with existing literature. Nevertheless, consistent with the literature, the technology received lower scores for user-friendliness (3.9 out of 5), suggesting usability improvements are critical for wider industry adoption. Blockchain technology showed alignment between the analysis and literature, particularly in scalability (4.36 out of 5), reliability (4.45 out of 5), data security, and privacy (4.7 out of 5). Its high-cost perception (4.45 out of 5) also matched literature insights. Conversely, both sources indicated potential user-friendliness challenges (3.91 out of 5), necessitating managerial strategies to enhance adoption ease.

ERP systems displayed strong alignment with literature, notably in scalability (4.55 out of 5) and perceived cost (4.45 out of 5). The analysis further indicated substantial strengths in accuracy (4.4 out of 5), com-

patibility (4.27 out of 5), and reliability (4.27 out of 5). However, user-friendliness presented a discrepancy, with the empirical analysis rating it moderately (4 out of 5), contrasting literature suggesting higher usability. Addressing these usability challenges will be essential for optimal ERP implementation.

The final rankings underscored barcode technology as the leading solution, achieving a performance score of 0.69935. Its superior user-friendliness and minimal equipment requirements underscore its practical advantages, particularly for industries prioritizing operational efficiency and economic viability. IoT closely followed barcode technology with a performance score of 0.52315. IoT's strengths lie in its real-time data identification capabilities and excellent scalability facilitating seamless integration within diverse operational contexts, despite being perceived as the most costly among the evaluated technologies (4.64 out of 5). Blockchain (0.448013), DNA Barcoding (0.386412), ERP (0.36834), and RFID (0.306274) followed respectively, each presenting unique trade-offs requiring strategic managerial consideration.

Overall, this study highlights barcode technology and IoT as particularly effective solutions for enhancing traceability in food manufacturing. Their combined advantages in affordability, ease of use, and adaptability align strongly with practical industry requirements and regulatory compliance goals. As firms continue prioritizing traceability to mitigate risks and bolster consumer trust, barcode technology and IoT present compelling strategic options, supporting both short-term operational effectiveness and long-term competitive advantage.

The study focused primarily on six novel technologies which are selected through literature and used in contemporary food manufacturing industries. However, there may be other emerging technologies or variations of existing ones that were not included in the analysis. This limited scope may restrict the comprehensiveness of the findings and overlook potentially viable alternatives. The findings of the study are based on a selected seven factors which may not apply to all food manufacturing industries. Factors such as industry sector, readability and customisability can significantly influence technology adoption and performance. Therefore, industries should be aware and cautious while selecting technologies according to different contexts.

The study utilised a TOPSIS approach for in-depth analysis. While the technique provides a systematic framework for decision-making, it depends on subjective expert judgments for criteria weighting and may be prone to bias. Additionally, the study's reliance on interviews with experts introduces a limited representativeness of industry perspectives. Furthermore, the

expert opinions used for criteria weighting introduce a level of subjectivity that could affect the rankings. Further research could expand on alternative decision-making frameworks and evaluate emerging technologies such as AI-driven traceability systems. The findings are contingent upon the availability and quality of data obtained from literature sources, journals, websites and expert interviews. Variability in data may introduce uncertainties into the analysis. Moreover, the study does not address the practical challenges and barriers associated with their implementation.

Another area for future exploration is the impact of regulatory policies on technology adoption. Different regions have varying compliance requirements, which can influence the feasibility of implementing certain technologies. Cost-benefit analyses for small- and medium-sized enterprises (SMEs) would also provide practical insights for businesses looking to adopt traceability solutions on a limited budget. Overall, while this study provides an effective food traceability technology, it is essential to consider these limitations when interpreting and applying them practically in the industries.

Drawing from the study results, several guidance can aid food manufacturing industries in selecting technology for food traceability. Firstly, the study underscores the barcode technology as a highly recommended solution. It stands out as an optimal choice due to its user-friendliness, making it easy for professionals to operate. Moreover, barcode technology offers an attractive proposition in terms of affordability, as it presents a cost-effective option for implementing it. Its reliability and scalability further boost it as a preferred solution, ensuring consistent performance and being able to link with the existing as well as the future technologies and demands.

Moreover, the study asserts that the Internet of Things is a feasible option for food traceability technology. IoT is prudent for its scalability, communication capabilities and data identification features which allows integration of IoT with the existing infrastructure and enhance data capture efficiency. While IoT may require a slightly higher initial investment compared to barcode technology, its long-term benefits in terms of enhanced traceability and operational efficiency justify the expenditure.

For industries prioritizing high data security and privacy requirements, Blockchain presents a viable option. Despite its complexity and relatively higher implementation costs, Blockchain offers unparalleled levels of data security and integrity, mitigating the risk of data tampering and unauthorized access.

DNA barcoding presents a tailored solution in scenarios where the traceability of specific products, such as meat, is of utmost importance. DNA barcoding's

exceptional accuracy in product identification and relatively lower cost than IoT implementations make it an ideal choice for industries seeking precise and cost-effective traceability solutions. Furthermore, the study emphasizes the significance of prioritizing reliability and scalability for selecting traceability technologies as they can accommodate future growth and evolving needs effectively. Leveraging the study's findings and collaborating with industry engineers and technology experts can offer valuable insights for the seamless integration of traceability systems.

Conclusions

This study presents a comprehensive evaluation of traceability technologies within the food manufacturing sector, underpinned by a systematic literature review, expert validation, and a rigorous application of the TOPSIS method. Through a multi-step approach, the research identified key traceability technologies and assessed them against economically and operationally relevant criteria (i.e. namely cost, accuracy, compatibility, reliability, scalability, data security, and user-friendliness). The methodological integration of expert insights with quantitative multi-criteria decision-making enabled a structured ranking of technologies based on their practical applicability and strategic value.

The study fulfilled its objectives in a sequential and evidence-driven manner. First, dominant traceability technologies (i.e. Barcode, RFID, Blockchain, IoT, DNA Barcoding, and ERP) were identified. Second, critical selection criteria were established through engagement with industrial experts. Finally, the TOPSIS model was employed to derive a ranked assessment that supports strategic technology adoption in food manufacturing contexts. The findings indicate that Barcode Technology and the Internet of Things (IoT) are the most effective traceability solutions, offering a favourable balance between economic feasibility and operational performance. These insights hold significant managerial implications. Barcode Technology, with its low cost, ease of use, and scalability, is particularly suitable for firms seeking quick deployment and minimal disruption to existing systems. IoT, while requiring more upfront investment, provides enhanced real-time visibility and data integration, supporting advanced decision-making across the supply chain. These technologies align with the industry's growing need to strengthen traceability in compliance with safety regulations, consumer expectations, and global quality standards.

Moreover, the study offers a valuable foundation for further academic and industrial inquiry. Future research could explore alternative decision-making methodologies, incorporate dynamic cost-benefit analyses, or evaluate the integration of hybrid traceability systems. Additionally, the inclusion of emerging technologies such as artificial intelligence or blockchain-IoT convergence could yield deeper insights into next-generation traceability models.

While the study contributes novel insights, it is not without limitations. The evaluation relied on a finite number of expert opinions and considered a selected subset of technologies and criteria. As such, the results may reflect context-specific interpretations and technological readiness levels. Nonetheless, the research remains robust in its alignment with extant literature and presents actionable recommendations for technology selection. Furthermore, this study assumes standalone technology adoption, whereas in practice traceability systems are often hybrid, combining multiple technologies, which may limit the real-world applicability of the findings. Future studies could address this limitation by evaluating hybrid traceability architectures or modelling multi-technology integration scenarios to better reflect industrial practice.

In conclusion, this study reinforces the strategic importance of traceability technologies in enhancing food safety, enabling efficient recall mechanisms, and building consumer trust. By applying the findings herein, food manufacturing firms can adopt data-driven, economically sound approaches to technology investment and deployment. It is anticipated that this research will catalyse further innovation and contribute to the global effort toward safer, more transparent food supply chains.

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