EASR

Engineering and Applied Science Research

https://www.tci-thaijo.org/index.php/easr/index

Published by the Faculty of Engineering, Khon Kaen University, Thailand

Enhancing sustainability and key success factors in digital food supply chain management through digital transformation: A fuzzy AHP approach

Sirorat Wiwatkajornsak* and Chayathach Phuaksaman

Department of Industrial Engineering, Faculty of Engineering, King Mongkut's University of Technology North Bangkok, Bangkok 10800, Thailand

Received 22 December 2024
Revised 16 March 2025
Accepted 25 March 2025

Abstract

This study investigated the key success factors in digital food supply chain management for Thailand's food retail industry through digital transformation, employing the Fuzzy Analytic Hierarchy Process (FAHP) for the integrated digital food supply chain model. Through an extensive literature review and expert consultations, the critical criteria were identified and ranked in the researched domains of digital strategy, digital operations management, digital customer experiences, and digital organization and culture management. Business alignment is the primary focus within digital strategy, followed by technology investments to enable this alignment and data-driven decision-making. Supply chain visibility is considered the most crucial aspect of digital operations management, and data analytics along with inventory management are integral aspects that lead to operational efficiency. In the realm of digital customer experiences, aspects of customer centricity, convenience and accessibility, and order tracking and communication are the top drivers of satisfaction and loyalty. Finally, leadership and vision are recognized as essential for digital organization and culture management, along with fostering digital skills, capabilities, agility, and adaptability. In addition, this study provides a practical framework for improving Thai food retail organizations through the alignment of engineering, organizational, and consumer expectations.

Keywords: Food supply chain management, Fuzzy AHP, Digital strategy, Digital operations management, Digital customer experiences, Digital organization and culture management

1. Introduction

The Thai food retail market is very diverse, including traditional wet markets, street food, convenience stores, supermarkets, hypermarkets, and online channels. Characterized by factors like urbanization, increasing disposable incomes, and changing consumer lifestyles, this industry is essential to the national economy. However, the growing consumer demand for convenience, quality and transparency has posed crucial challenges to food retailers in Thailand who need to adjust to the changing landscape while ensuring efficiency and sustainability.

[1] Research highlights Thailand's food retail market as an attractive investment destination due to economic growth, with digital transformation gaining traction through smartphone applications and online shopping. The evolution from the traditional paradigms of food supply chain management to more modern approaches has paved the way for digitization and analytics driven by digital transformation. Consequently, numerous opportunities and challenges have been created for food retail businesses in recent years. Digital technologies can unlock opportunities to improve efficiencies, drive operational prowess, and enable transparency. However, many businesses in Thailand's food retail sector have struggled to maximize the potential of these technologies. The shift from traditional food supply chain management to modern, digital-driven approaches has created both opportunities and challenges for Thailand's food retail sector. While digital technologies enhance efficiency, transparency, and operational effectiveness, many businesses struggle to fully capitalize on these advancements [2]. While supermarkets can leverage data analytics for procurement and inventory management, fresh markets often lack digital integration, making it harder for them to meet rising consumer expectations for convenience, reliability, and food safety. Challenges such as supply chain limitations, inventory control issues, and intense competition from affordable e-commerce stocks further hinder digital adoption. Without a clear digital strategy, inefficiencies persist across operations, customer engagement, and organizational structure. Addressing these challenges requires a comprehensive digital strategy to ensure sustainable competitiveness in the evolving retail landscape.

Despite the growing importance of digital transformation in modern supply chains, comprehensive research on its impact within the food industry remains inadequate. The absence of sufficient data and insights hinders the development of strategic approaches for achieving successful food supply chain management through digital transformation.

Additionally, there is a gap in assessing the readiness of businesses to adopt digital transformation for planning and improving food supply chain operations. Understanding the level of preparedness is crucial for ensuring a smooth transition and effective implementation of digital strategies. Furthermore, there is a lack of structured evaluation in terms of the key success factors influencing

*Corresponding author.
Email address: sirorat.w@email.kmutnb.ac.th
doi: 10.14456/easr.2025.29

digital transformation in food supply chain management. Prior studies have not systematically ranked these factors based on their impact, leaving a critical gap in identifying which elements contribute most significantly to a successful transformation process.

This research aims to address the gaps by leveraging a Fuzzy AHP approach to enhance sustainability and determine the key success factors for digital food supply chain management. The results of this research will provide significant benefits to the food retail industry in Thailand. In an era of rapid changes and intense competition, identifying key success factors in digital food supply chain management is crucial for driving successful digital transformation. These factors play a vital role in enabling organizations to adapt, enhance operational efficiency, and maintain competitiveness while responding to evolving consumer demands. Additionally, this study aims to provide practical insights and best practices that food retailers can adopt to improve business resilience, operational performance, and long-term sustainability in the digital age.

2. Digital industry 4.0 for food supply chain management

Digital Industry 4.0 is revolutionizing supply chain management (SCM) across various sectors, including the food industry, by integrating advanced digital technologies such as IoT, artificial intelligence (AI), big data, blockchain, and robotics [3, 4] to enhance efficiency, transparency, and adaptability. Traditional SCM has evolved from fragmented data management to real-time data sharing, enabling seamless coordination among supply chain partners. The successful implementation of SCM requires Supply Chain Orientation (SCO), supported by top management and collaboration between stakeholders, where trust plays a critical role in fostering agility and resilience.

Industry 4.0 technologies are essential for integrating producers and consumers through developing efficient, safe, environmentally friendly, and sustainable approaches, which requires addressing challenges such as food safety, perishability, and varying demands in the food industry. The power of predictive analytics aids in the demand for forecasting, while AI enhances production efficiency via automation, blockchain allows secure and transparent transactions, and cloud computing (CC) offers real-time data accessibility. These efficiencies help ensure appropriate inventory control, improve traceability through compliance to the food safety guidelines, and streamline logistics while reducing operational costs as well as food waste.

In contrast to the aforementioned, challenges such as high investment costs, a lack of skilled personnel, and resistance to change hinder widespread adoption, particularly for small businesses. For instance, financial constraints and limited access to skilled labor in Thailand’s sugar industry impede digital transformation, despite the potential to reduce costs and improve decision-making through data analytics [5]. To effectively implement Industry 4.0 in the food industry, companies must develop a digital strategy, invest in workforce training, and leverage government support for infrastructure development. A well-executed digital transformation strengthens food supply chain resilience, enhances competitive advantage, ensures food quality and safety, and supports sustainability initiatives in dynamic market conditions.

2.1 Digital food supply chain management (DFSCM)

In the food retail industry, digital supply chain management applies advanced technology to every aspect of the supply chain, from forecast and inventory management to consumer experience. Some key applications include real-time tracking, demand forecasting, route optimization and blockchain-enabled transparency [6]. IoT/RFID/data analytics and others enable the execution of real-time monitoring, predictive decision-making, and risk mitigation.

These technologies drive operational efficiency, customer satisfaction, and sustainability by ethically sourcing and minimizing food waste. With data, it is also possible to allow food retailers to be agile and keep up with changing market demands, optimizing their supply chains and providing extra value to their customers in a responsible way.

2.2 Digital strategy

Digital supply chain management is grounded in a strong digital strategy that will determine how technologies are leveraged to help the business achieve its target objectives. Some key success factors in digital adoption are related to operational improvement, strategic alignment, customer demand, supplier pressure, and competition [7]. An effective strategy further improves efficiency, market differentiation, and innovation, which helps organizations in adopting digitalization and meeting operational goals [8]. Technological intelligence and supply chain collaboration are striving to maximize the digital initiatives [7]. A holistic perspective on digital strategy connects technology, customers, and organizational focuses [9], promoting a culture change that transforms conventional supply chains into quick, agile, linked, community-like digital ecosystems [3]. It helps food retailers fulfill the changing needs of consumers, prepare for change, and take advantage of technology to remain competitive and agile over the long term.

2.3 Digital operation management

A digitalization strategy supports system integration and distinctive data-driven processes along the food supply chain. For this purpose, IoT, blockchain, and BDA are used in digital operations management to improve inventory, production, logistics, and supply chain visibility [10, 11]. Thus, it is possible to carry out predictive planning, the reduction of waste and operational efficiency by combining sensor data (IoT), big data (AI, cloud) and digital traceability (RFID) [9, 12]. Digital platforms support collaboration among stakeholders for resource sharing and sustainability. Organizations utilizing these tools benefit from enhanced productivity, reduced costs, satisfied customers, and quick adaptation to market changes [3, 10, 12, 13]. In the digital age, the digital operations are indispensable for the realization of agile, efficient, and competitive supply chains [3, 14].

2.4 Digital customer experiences

Digital customer experience in the food supply chain manifests as contact points with consumers through web platforms, web apps, and service portals that enable the promoting of convenience, personalization, transparency, and responsiveness [15]. Emerging technologies such as the IoT, CC, and big data analytics allow for real-time tracking, personalized interactions, and transparency of product sourcing, which helps to build trust and satisfaction [16]. Therefore, a well-designed digital customer experience can positively impact brand loyalty and market differentiation as well as leads to sustainable supply chain performance [15, 16]. This notion is centered on providing personalized and attentive interactions that increase customer satisfaction and the success of the entire organization [17]. It also represents an essential part of digital supply chain management through increased engagement, personalization and responsiveness [9].

2.5 Digital organization and culture management

Digital organization and culture management are drivers of change in the food supply chain, encouraging technological innovation while making it possible to act or react rapidly, often in a collaborative manner [18]. A cultural shift towards digital goals enables successful adoption of digital technologies across supply chains, boosting supply chain efficiency, resilience and competitiveness in the market [9, 19]. Knowledge Management (KM) helps with the transfer of knowledge and adaptation of Industry 4.0 technologies, allowing firms to utilize advanced digital technologies [19]. Digital supply chain transformation that considers the role of people, processes, and technology represents the true transformational aspect of effective digital organization and culture management [9].

Recent studies on the integration of digital technologies in food supply chain management are summarized in Table 1.

Table 1 Summary of literature on Digital Food Supply Chain Management

Articles	Digital Strategy	Digital Operations management	Digital Customer Experiences	Digital Organization and Culture Management
Garay-Rondero et al. [3]	/	/		
Ho et al. [8]	/			
Ageron et al. [9]	/	/	/	/
Büyüközkan and Göçer [14]		/		
Deepu and Ravi [15]		/		
Bui et al. [18]			/	/
Queiroz and Wamba [20]		/		
Bejlegaard et al. [21]	/			
This study	/	/	/	/

3. Material and methods

3.1 Statement of the problem

The adoption of digital innovations in food retail can be pivotal for supply chain trends as well as the sustainability of food retail in general. However, organizations need a comprehensive understanding of what drives sustainability and competitiveness in order to succeed with digital transformation initiatives.

The primary challenge for the food retail industry is identifying and prioritizing the determinants of success that are critical for driving sustainability through digital transformation in food supply chain management. There is an urgent imperative to distinguish the different areas of engagement within the fields of digital strategy, digital operations management, digital customer experiences, and digital organization and culture management that matter most for sustainable outcomes. The evaluation framework consists of four key criteria with well-defined sub-criteria to ensure clarity in interpretation. Digital strategy focuses on aligning technology with business goals to drive growth, covering alignment with business objectives, technology investment decisions, risk management and mitigation, adaptation to market trends, differentiation and innovation and data-driven decision making. Digital operations management involves managing digital processes in production, procurement, and customer service to enhance efficiency and performance. Key areas include supply chain visibility, production optimization, quality control, logistics and transportation, inventory management, data analytics, and insights and waste management. Digital customer experiences enhance customer interactions through convenience, personalization, and trust-building in the digital era. It covers convenience and accessibility, personalization, transparency and traceability, customer-centricity, order tracking and communication, customer support and assistance, brand loyalty and advocacy and e-commerce and direct-to-consumer channels. Digital organization and culture management focus on developing a digitally adaptive organization with strong leadership, agile structures, and innovation-driven cultures. It includes leadership and vision, agility and adaptability, digital skills and capabilities, change management, collaboration and communication, organizational structure, and innovation and experimentation.

This study employed a structured interview with 12 experts in the food supply chain sector to ensure the reliability and validity of the data. The selection criteria for these experts included (1) holding a managerial position in supply chain operations, planning, or logistics, (2) possessing at least ten years of experience in the food retail industry, and (3) having direct involvement in digital transformation initiatives within supply chain management. The panel consisted of operation managers (6 experts) and planning managers (6 experts) from leading food retail companies in Thailand, ensuring a balanced representation of perspectives from both operational and strategic planning domains. Their expertise spans inventory management, procurement, logistics optimization, demand forecasting, and digital supply chain integration, which are critical aspects relevant to this study. The interview questionnaire was built along the lines of a Likert scale to facilitate a scored response from the participants that reflects their perception about the various factors driving the digital transformation of food supply chain management. To assess the internal consistency and reliability of the responses obtained, Cronbach's alpha (α) was employed as the reliability test metric, with a value of 0.7 or higher being considered acceptable. Digital strategy alternatives have a reliability score of 0.75, while digital operation management is 0.755, digital customer experiences is 0.792, and digital organization and culture management is 0.711. Criteria and alternative symbols are given in Table 2.

Table 2 List of sub-criteria and symbols

Criteria	Symbols	Alternatives	References
Digital Strategy (DS)	A1	Alignment with Business Objectives	[22]
	A2	Technology Investment Decisions	[23]
	A3	Risk Management and Mitigation	[24]
	A4	Adaptation to Market Trends	[25, 26]
	A5	Differentiation and Innovation	[27]
	A6	Data-Driven Decision Making	[28]
Digital Operations Management (DOM)	B1	Supply Chain Visibility	[11, 29]
	B2	Production Optimization	[28]
	B3	Quality Control	[30]
	B4	Logistics and Transportation	[28]
	B5	Inventory Management	[28]
	B6	Data Analytics and Insights	[3, 4]
	B7	Waste Management	[31, 32]
Digital Customer Experiences (DCE)	C1	Convenience and Accessibility	[33]
	C2	Personalization	[34, 35]
	C3	Transparency and Traceability	[22]
	C4	Customer-Centricity	[36]
	C5	Order Tracking and Communication	[33, 35]
	C6	Customer Support and Assistance	[33, 35]
	C7	Brand Loyalty and Advocacy	[35, 37]
	C8	E-commerce and Direct-to-Consumer Channels	[22, 38]
Digital Organization and Culture Management (DOC)	D1	Leadership and Vision	[39]
	D2	Agility and Adaptability	[40]
	D3	Digital Skills and Capabilities	[6, 41, 42]
	D4	Change Management	[43]
	D5	Collaboration and Communication	[44]
	D6	Organizational Structure	[45]
	D7	Innovation and Experimentation	[46]

3.2 Fuzzy AHP methodology

The Fuzzy Analytic Hierarchy Process (FAHP) combines the traditional Analytic Hierarchy Process (AHP), developed by Thomas Saaty in the 1980s, with the fuzzy set theory introduced by Lotfi Zadeh in 1965, thus addressing AHP's limitation of relying on precise numerical judgments by incorporating fuzzy numbers to handle uncertainty and imprecision in subjective evaluations [47]. This hybrid methodology involves structuring decision problems hierarchically, using fuzzy pairwise comparison matrices to express preferences, aggregating fuzzy judgments (particularly in group decision-making), defuzzifying to generate crisp scores, and evaluating the consistency of judgments. FAHP provides flexibility in articulating preferences, making it a valuable tool for multi-criteria decision-making in various fields like supplier selection and project evaluation [48]. FAHP enables decision-makers to incorporate subjective judgments into a structured decision-making process, enhancing the reliability of decisions in complex and uncertain environments.

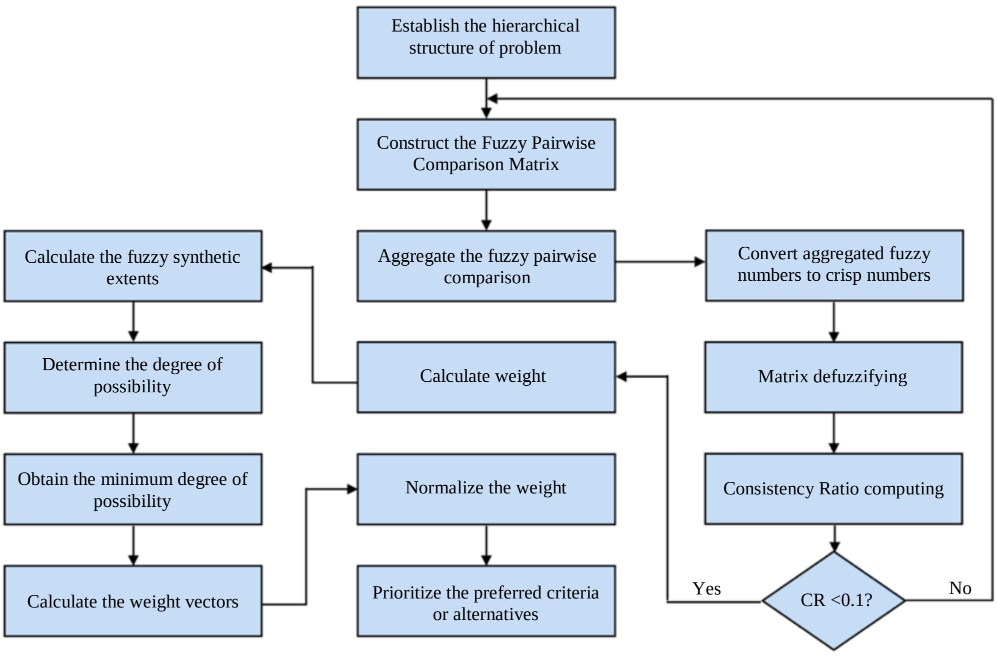

Figure 1 Fuzzy analytical hierarchy process flowchart

The practical implementation of FAHP involves a structured approach, as in Figure 1.

1. Formulate a hierarchical evaluation questionnaire to convert decision-maker's judgments into fuzzy triangular numbers.

2. When expressing judgments using fuzzy triangles, decision-makers convey their preferences through linguistic variables and qualitative terms that can be transformed into numerical values for analysis [49]. These preferences are then translated into equivalent fuzzy triangular values, as shown in Table 3. Additionally, the scale of fuzzy numbers [50] allows decision-makers to express their evaluations using linguistic terms, which are then converted into triangular fuzzy numbers. This conversion helps address the vagueness and subjectivity involved in the decision-making process, as illustrated in Figure 2. Triangular Fuzzy Numbers are one of the most used forms of fuzzy representation, often applied to express uncertainty or ambiguity in data. They are defined by three points including l, m, and u, representing the lower, middle, and upper values, respectively. Fuzzy logic handles uncertainty and imprecision. It serves as a foundation for various models and applications across multiple fields, such as transportation data analysis, decision-making under uncertainty, and algebraic structures.

3. Once the hierarchy is established and pairwise comparisons of alternative criteria are conducted, the priority weights for each alternative are computed.

Table 3 Linguistic terms for triangular fuzzy numbers

Linguistic variables	**Triangular fuzzy scale**
Equally Impact	(1,1,1)
Intermediate Equally Impact	(1,2,3)
Moderately Impact	(2,3,4)
Intermediate Moderately Impact	(3,4,5)
Strongly Impact	(4,5,6)
Intermediate Strongly Impact	(5,6,7)
Very Strong Impact	(6,7,8)
Intermediate Very Strongly Impact	(7,8,9)
Extremely Impact	(8,9,9)

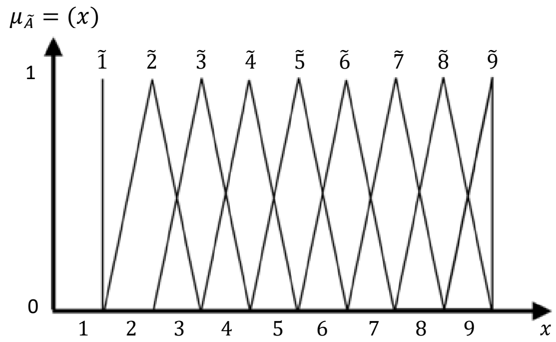

Figure 2 Scale of fuzzy numbers

Identifying key success factors and improving sustainability in the digital food supply chain management problem can be addressed using the FAHP method, which is a suitable approach that can deal with uncertainty and subjective nature in such problems. Decision-makers are often intimidated by the complex and multifaceted nature of the criteria that must be balanced, including digital strategy, digital operations management, digital customer experiences, and digital organization and culture management. Fuzzy AHP is particularly suited for this study as it combines the clear hierarchical structure of AHP with fuzzy logic to more effectively handle uncertainty in expert assessments. Digital food supply chain management is highly complex and constantly evolving, making expert opinions inherently uncertain. By leveraging fuzzy numbers, FAHP allows for a more flexible and precise evaluation of key factors, reducing the limitations of crisp value methods. This approach enhances the reliability of prioritization by accommodating ambiguity in expert judgments, ensuring a more accurate reflection of stakeholder perspectives in digital transformation decision-making.

This study examines the adoption of digital food supply chain management in the context of the food retail sector, using the FAHP to gain insight. Following a holistic approach, the qualitative data were collected through interviews with five industry professionals, each of which had more than a decade of experience in their domain. These individuals were chosen independently from those assessing the reliability testing, which provided neutral viewpoints. These experts represented operations managers, planning managers, and experts in managing the digitalization of the food supply chain. Having had decades of experience, they were able to understand both the strategic and operational issues underlying the adoption of digital solutions and effectiveness of the literature before conducting an in-depth analysis of the critical drivers impacting the adoption and effectiveness of digital solutions.

Using an FAHP approach, organizations within the food retail industry can more effectively assess and rank the various key success factors, facilitating evidence-based decision-making and strategic planning to promote sustainable developments and advancements in the digital food supply chain management landscape, following a structured process utilizing the FAHP model with criteria significance weights, as shown in Figure 3.

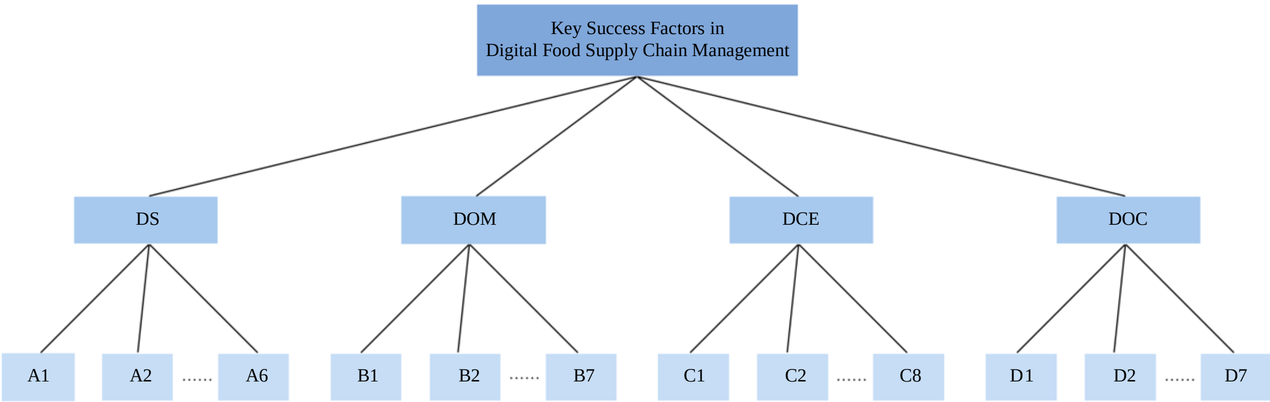

Figure 3 Hierarchy of the digital food supply chain management problem

3.2.1 Construction of the fuzzy pairwise comparison matrix

Pairwise comparison is a fundamental process within decision-making methodologies such as the AHP and its fuzzy variant, FAHP. It involves systematically comparing each criterion or alternative against every other criteria or alternative to establish their relative importance or preference.

Matrix comparison,

$$\tilde{A}=(\tilde{a}_{ij})_{n\times n}=\begin{bmatrix} (1,1,1) & (l_{12},m_{12},u_{12}) & \cdots & (l_{1n},m_{1n},u_{1n}) \\ (l_{21},m_{21},u_{21}) & (1,1,1) & \cdots & (l_{2n},m_{2n},u_{2n}) \\ \vdots & \vdots & \vdots & \vdots \\ (l_{n1},m_{n1},u_{n1}) & (l_{n2},m_{n2},u_{n2}) & \cdots & (1,1,1) \end{bmatrix} \tag{1}$$

Where

$$\tilde{a}_{ij}=(l_{ij},m_{ij},u_{ij}) \tag{2}$$

For reciprocal

$$\tilde{a}_{ij}^{-1}=\left(\frac{1}{u_{ij}},\frac{1}{m_{ij}},\frac{1}{l_{ij}}\right), \text{ for } i,j=1,\ldots,n \text{ and } i\neq j \tag{3}$$

3.2.2 Aggregate the fuzzy pairwise comparisons

The fuzzy geometric mean method combines the judgments from all experts. Geometric mean in FAHP enhances decision-making under uncertainty by effectively aggregating expert opinions while minimizing the impact of outliers, ensuring more reliable results. It maintains reciprocity in pairwise comparisons, preserves consistency, and systematically handles ambiguity in fuzzy-weighted criteria. With clear and repeatable calculations, it facilitates efficient evaluation and comparison of alternatives. Additionally, its flexibility allows decision-makers to dynamically adjust weights based on new data, making it highly adaptable to changing conditions. The aggregated fuzzy number for pairwise comparison is calculated from Eqn. (4-7).

$$\tilde{C}^{ij}=(l_{ij},m_{ij},u_{ij}) \tag{4}$$

And

$$l_{ij}=\left(\prod_{k=1}^{n} l_{ij}^{k}\right)^{\frac{1}{n}} \tag{5}$$

$$m_{ij}=\left(\prod_{k=1}^{n} m_{ij}^{k}\right)^{\frac{1}{n}} \tag{6}$$

$$u_{ij}=\left(\prod_{k=1}^{n} u_{ij}^{k}\right)^{\frac{1}{n}} \tag{7}$$

Where l_{ij}^{k}, m_{ij}^{k} and u_{ij}^{k} are the lower, middle, and upper of the fuzzy number provided by k experts between criteria i and j. Convert aggregate fuzzy weights numbers into crisp numbers from Eqn. (8).

$$W_i=\frac{l_i+m_i+u_i}{3} \tag{8}$$

3.2.3 Calculate the fuzzy synthetic extent value

For the fuzzy synthetic extent value S_i for criteria, follow Eqn. (9).

$$S_i=\sum_{j=1}^{m} M_{gi}^{j} \otimes \left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^{j}\right]^{-1} \tag{9}$$

The triangular fuzzy values M_{gi}^{i} can be calculated from Eqn. (10-12).

$$\sum_{j=1}^{m} M_{gi}^{j} =\left[\sum_{j=1}^{m} l_j , \sum_{j=1}^{m} m_j , \sum_{j=1}^{m} u_j\right]^{-1} \tag{10}$$

And

$$\left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^{j}\right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n} u_i}, \frac{1}{\sum_{i=1}^{n} m_i}, \frac{1}{\sum_{i=1}^{n} l_i}\right) \tag{11}$$

And

$$\sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^{j} =\left(\sum_{i=1}^{n} l_i , \sum_{i=1}^{n} m_i , \sum_{i=1}^{n} u_i\right) \tag{12}$$

3.2.4 Calculate the degree of possibility

The degree of possibility for $S_i \geq S_j$, [51] intersects between $\widetilde{M}_1$ and $\widetilde{M}_2$ in Figure 4.

Where $S_i = (l_i, m_i, u_i)$,$S_j = (l_j, m_j, u_j)$;$i\neq j$ calculated from Eqn. (13).

$$V(S_i\geq S_j)=\begin{cases} 1 & m_i\geq m_j \\ 0 & l_j\geq u_i \\ \frac{(l_j-u_i)}{(m_i-u_i)-(m_j-l_j)} & \text{other} \end{cases} \tag{13}$$

Convex fuzzy number $S_i \geq S_j$ where $i \neq j$ and $i = 1,2,\ldots,n$ from Eqn. (14).

$$V(S_i \geq S_j \mid j=1,2,\ldots,n;i\neq j)=\min V(S_i \geq S_j) \tag{14}$$

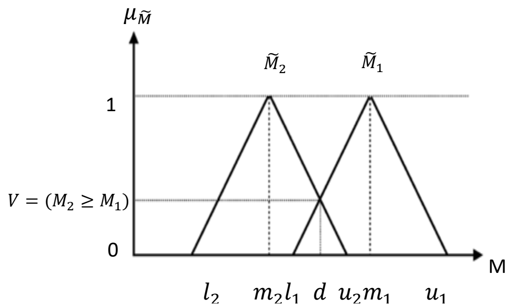

Figure 4 Degree of possibility of $V(S_i\geq S_j)$

3.2.5 Determine the weight vector

The weight vector W is derived by normalizing the degree of possibility, indicated from Eqn. (15).

$$W_i=\frac{V(S_i \geq S_j)}{\sum_{i=1}^{n} V(S_i \geq S_j)} \tag{15}$$

3.2.6 Calculate the Consistency Index (CI) and the Consistency Ratio (CR)

The consistency index (CI) is calculated by using Eq. (16) where λ_{max} is the largest eigenvalue of the comparison matrix and n is the number of criteria. CR should be ≤ 0.1, the consistency is acceptable, and RI is the random consistency index, as shown in Table 4 and calculated by using Eq. (17).

$$CI= \frac{(\lambda max-n)}{n-1} \tag{16}$$

The consistency ratio

$$CR= \frac{CI}{RI} \tag{17}$$

Table 4 Random Consistency Index (RI)

N	1	2	3	4	5	6	7	8
RI(n)	0	0	0.52	0.89	1.12	1.25	1.34	1.4

4. Results and discussion

The experimental results show the key success factors in digital food supply chain management. In this study, the relative importance of the key success factors in digital food supply chain management was assessed using the extent analysis method.

To aggregate the fuzzy number for pairwise comparison of criteria calculated from Eqn. (4-7). The results of the aggregated fuzzy pairwise comparison of criteria and alternatives are shown in Figure 5. The results of criteria and alternatives for digital food supply chain management are given in Tables 5 and 6.

Aggregate the fuzzy pairwise comparison of criteria

Criteria	DS	DOM	DCE	DOC
DS	(1,1,1)	(1.64,2.7,3.73)	(2,3,4)	(2,3,4)
DOM	(0.27, 0.37, 0.61)	(1,1,1)	(1,2,3)	(1.78, 2.86, 3.89)
DCE	(0.25, 0.33, 0.5)	(0.33,0.5,1)	(1,1,1)	(0.37, 0.56, 0.94)
DOC	(0.25, 0.33, 0.5)	(0.26, 0.35, 0.56)	(1.06, 1.78, 2.7)	(1,1,1)

Aggregate the fuzzy pairwise comparison of digital strategy alternative.

	A1	A2	A3	A4	A5	A6
A1	(1, 1, 1)	(2.35,3.37,4.37)	(2, 3, 4)	(2.55,3.57,4.57)	(1.15, 2.17, 3.18)	(1.52, 2.56, 3.57)
A2	(0.23,0.29,0.43)	(1, 1, 1)	(2, 3, 4)	(1.15, 2.17, 3.18)	(1.32, 2.35, 3.37)	(1.15, 2.17, 3.18)
A3	(0.25, 0.33, 0.5)	(0.25, 0.33, 0.5)	(1, 1, 1)	(1.32, 2.35, 3.37)	(1.15, 2.17, 3.18)	(0.45, 0.66, 1.15)
A4	(0.22, 0.28, 0.39)	(0.32, 0.46, 0.88)	(0.29, 0.43, 0.76)	(1, 1, 1)	(1, 2, 3)	(0.32, 0.46, 0.87)
A5	(0.32, 0.46, 0.87)	(0.29, 0.43, 0.76)	(0.32, 0.46, 0.87)	(0.33, 0.5, 1)	(1, 1, 1)	(0.37, 0.56, 0.94)
A6	(0.28, 0.39, 0.66)	(0.32, 0.46, 0.87)	(0.87, 1.52, 2.22)	(1.15, 2.17, 3.18)	(1.06, 1.78, 2.7)	(1, 1, 1)

Aggregate the fuzzy pairwise comparison of digital operations management alternative.

	B1	B2	B3	B4	B5	B6	B7
B1	(1, 1, 1)	(1.32,2.35,3.37)	(1.52,2.55,3.57)	(1, 2, 3)	(1, 2, 3)	(0.33, 0.5, 1)	(1.15,2.17,3.18)
B2	(0.28,0.43,0.76)	(1, 1, 1)	(1, 2, 3)	(0.32,0.46,0.87)	(0.33, 0.5, 1)	(0.32,0.46,0.87)	(1, 2, 3)
B3	(0.28,0.39,0.66)	(0.33, 0.5, 1)	(1, 1, 1)	(1, 2, 3)	(0.29,0.43,0.76)	(0.27,0.36,0.57)	(1, 2, 3)
B4	(0.33, 0.5, 1)	(1.15,2.17,3.18)	(0.33, 0.5, 1)	(1, 1, 1)	(1, 2, 3)	(1, 2, 3)	(1, 2, 3)
B5	(0.33, 0.5, 1)	(1, 2, 3)	(1.32,2.35,3.37)	(0.33, 0.5, 1)	(1, 1, 1)	(1, 2, 3)	(1.52,2.55,3.57)
B6	(1, 2, 3)	(1.15,2.17,3.18)	(1.74,2.77,3.78)	(0.33, 0.5, 1)	(0.33, 0.5, 1)	(1, 1, 1)	(1, 2, 3)
B7	(0.32,0.46,0.87)	(0.33, 0.5, 1)	(0.33, 0.5, 1)	(0.33, 0.5, 1)	(0.28,0.39,0.66)	(0.33, 0.5, 1)	(1, 1, 1)

Aggregate the fuzzy pairwise comparison of digital customer experiences alternative.

	C1	C2	C3	C4	C5	C6	C7	C8
C1	(1, 1, 1)	(2, 3, 4)	(2, 3, 4)	(0.33,0.5,1)	(1, 2, 3)	(1, 2, 3)	(1, 2, 3)	(1, 2, 3)
C2	(0.25,0.3,0.5)	(1, 1, 1)	(2, 3, 4)	(0.25,0.3,0.5)	(0.33,0.5,1)	(0.33,0.5,1)	(2, 3, 4)	(1, 2, 3)
C3	(0.25,0.3,0.5)	(0.25,0.3,0.5)	(1, 1, 1)	(0.25,0.3,0.5)	(0.25,0.3,0.5)	(0.25,0.3,0.5)	(1, 2, 3)	(0.33,0.5,1)
C4	(1, 2, 3)	(2, 3, 4)	(2, 3, 4)	(1, 1, 1)	(1, 2, 3)	(1.7,2.8,3.8)	(2, 3, 4)	(2, 3, 4)
C5	(0.33, 0.5,1)	(1, 2, 3)	(2, 3, 4)	(0.33, 0.5, 1)	(1, 1, 1)	(0.5,0.7,1.2)	(1, 2, 3)	(1, 2, 3)
C6	(0.33,0.5, 1)	(1, 2, 3)	(2, 3, 4)	(0.3,0.4,0.6)	(0.9,1.4,2.2)	(1, 1, 1)	(1.2, 2.2,3.2)	(0.33,0.5,1)
C7	(0.33,0.5,1)	(0.25,0.3,0.5)	(0.33,0.5,1)	(0.25,0.3,0.5)	(0.33, 0.5,1)	(0.3,0.5,0.87)	(1, 1, 1)	(0.33,0.5,1)
C8	(0.33,0.5,1)	(0.33,0.5, 1)	(1, 2, 3)	(0.25,0.3,0.5)	(0.33, 0.5,1)	(1, 2, 3)	(1, 2, 3)	(1, 1, 1)

Aggregate the fuzzy pairwise comparison of digital organization and culture management alternative.

	D1	D2	D3	D4	D5	D6	D7
D1	(1, 1, 1)	(2.05, 3.1,4.13)	(1, 2, 3)	(2, 3, 4)	(2, 3, 4)	(1.74,2.77,3.78)	(2, 3, 4)
D2	(0.24,0.32,0.49)	(1, 1, 1)	(0.333, 0.5, 1)	(1, 2, 3)	(1, 2, 3)	(1.74,2.77,3.78)	(2, 3, 4)
D3	(0.33, 0.5, 1)	(1, 2, 3)	(1, 1, 1)	(1, 2, 3)	(1, 2, 3)	(1.32,2.35,3.37)	(2, 3, 4)
D4	(0.25, 0.33,0.5)	(0.33, 0.5, 1)	(0.333, 0.5, 1)	(1, 1, 1)	(1, 2, 3)	(1.15,2.17,3.18)	(2, 3, 4)
D5	(0.25, 0.33,0.5)	(0.33, 0.5, 1)	(0.333, 0.5, 1)	(0.33, 0.5, 1)	(1, 1, 1)	(1.32,2.35,3.37)	(1, 2, 3)
D6	(0.27,0.36,0.58)	(0.27,0.36,0.57)	(0.29,0.43,0.76)	(0.32,0.46,0.87)	(0.29,0.43,0.76)	(1, 1, 1)	(0.48,0.7,1.3)
D7	(0.25, 0.33,0.5)	(0.25, 0.33,0.5)	(0.25, 0.33,0.5)	(0.25, 0.33,0.5)	(0.33, 0.5, 1)	(0.76, 1.4, 2.1)	(1, 1, 1)

Figure 5 Aggregate the fuzzy pairwise comparison of criteria and alternatives

Table 5 Results of criteria for digital food supply chain management

Criteria	Weight	Prioritize	CR
Digital Strategy (DS)	0.4318	**1**	0.075
Digital Operations Management (DOM)	0.3286	**2**	
Digital Customer Experiences (DCE)	0.2087	**3**	
Digital Organization and Culture Management (DOC)	0.0309	4	

Table 6 Results of alternatives for criteria

Criteria		Alternatives	Weight	Prioritize	CR
DS	A1	Alignment with Business Objectives	0.3352	**1**	0.089
	A2	Technology Investment Decisions	0.2572	**2**	
	A3	Risk Management and Mitigation	0.1499	4	
	A4	Adaptation to Market Trends	0.0696	5	
	A5	Differentiation and Innovation	0.0181	6	
	A6	Data-Driven Decision Making	0.1697	**3**	
DOM	B1	Supply Chain Visibility	0.1819	**1**	0.097
	B2	Production Optimization	0.1244	5	
	B3	Quality Control	0.1205	6	
	B4	Logistics and Transportation	0.1625	4	
	B5	Inventory Management	0.1687	**3**	
	B6	Data Analytics and Insights	0.169	**2**	
	B7	Waste Management	0.073	7	
DCE	C1	Convenience and Accessibility	0.179	2	0.07
	C2	Personalization	0.1289	5	
	C3	Transparency and Traceability	0.0706	7	
	C4	Customer-Centricity	0.2088	1	
	C5	Order Tracking and Communication	0.1446	3	
	C6	Customer Support and Assistance	0.1346	4	
	C7	Brand Loyalty and Advocacy	0.0228	8	
	C8	E-commerce and Direct-to-Consumer Channels	0.1106	6	
DOC	D1	Leadership and Vision	0.2704	**1**	0.06
	D2	Agility and Adaptability	0.1968	**3**	
	D3	Digital Skills and Capabilities	0.2163	**2**	
	D4	Change Management	0.1635	4	
	D5	Collaboration and Communication	0.1195	5	
	D6	Organizational Structure	0.0132	7	
	D7	Innovation and Experimentation	0.0201	6	

5. Conclusions

This research highlights the importance of digital transformation to improve sustainability and identifies the success factors in digital food supply chain management. Based on the Fuzzy AHP approach, four dimensions were found to be critical: digital strategy, digital operations management, digital customer experiences, and digital organization and culture management.

However, a robust digital strategy also helps align business objectives, make informed technology investments, and facilitate data-driven decisions. Digital operations management is responsible for the visibility of the supply chain, its data analytics for efficiency, and the optimization of inventory for sustainability. Digital customer experience is performance-focused and prioritizes customer-centricity, convenience, and real-time tracking to instill loyalty. Leadership, digital skills, and agility empower a digital organization and culture. These factors further streamline processes and improve customer satisfaction as well as build competitiveness, ultimately contributing to a more agile, sustainable and adaptable food supply chain.

The study aligns with [9] research by exploring and developing a Digital Supply Chain (DSC) management framework that integrates emerging technologies to address organizational challenges. Key strategies include (1) integrating technologies like IoT, Big Data, and Cloud Computing to enhance efficiency, (2) developing digital skills for employees to adapt to rapid changes, (3) fostering an agile organizational culture to respond to market demands, (4) implementing performance measurement systems considering technology's role in DSC, and (5) analyzing consumer-supplier relationships to identify market opportunities. Additionally, it supports [3] findings on Industry 4.0 supply chain management, emphasizing (1) the digital transformation of supply chains requiring advanced planning and technology adoption, (2) the role of organizational culture and customer experience in leveraging technology for better services, and (3) a three-step implementation approach focusing on customer experience, digital value chain investment, and smart factory development.

The evaluation results help businesses in the food supply chain identify their strengths and weaknesses, thus enabling them to fine-tune their strategies and operations in alignment with industry trends. Implementing AI, IoT, Blockchain, and Digital Platforms can enhance efficiency, reduce costs, and improve long-term customer satisfaction.

For instance, a business that aims to strengthen its digital strategy should focus on aligning its digital transformation efforts with organizational goals by investing in technologies that enhance competitiveness. Leveraging AI and Big Data for data-driven decision-making can improve strategic planning and market responsiveness, such as developing e-commerce platforms and direct-to-consumer channels to adapt to market trends.

On the other hand, a business that seeks to improve its Digital Customer Experiences (DCE) should enhance its customer-centricity and transparency, which are crucial for customer satisfaction. Developing omni-channel platforms can improve convenience and accessibility, ensuring that customers can easily access products and services.

The findings of this research could be applied to other industries with complex supply chain structures that require digital technologies to enhance efficiency, such as manufacturing, retail, and pharmaceuticals. The concepts of Digital Strategy (DS), Digital Operations Management (DOM), Digital Customer Experiences (DCE), and Digital Organization and Culture Management (DOC) help businesses refine strategies, optimize processes, and improve customer experiences. However, industry-specific differences determine how these concepts are implemented. For example, the manufacturing sector emphasizes automation and IoT, while the pharmaceutical industry focuses on traceability and regulatory compliance, and the retail industry leverages AI and Big Data to analyze customer behavior. Key limitations include infrastructure readiness, technology adoption, and workforce capabilities. Therefore, applying these research findings necessarily requires adaptation to the unique context of each industry.

6. References

[1] Shannon R. The expansion of modern trade food retailing in Thailand. Int Rev Retail Distrib Consum Res. 2014;24(5):531-43.
[2] Banwell C, Kelly M, Dixon J, Seubsman SA, Sleigh A. Trust: the missing dimension in the food retail transition in Thailand. Anthropol Forum. 2016;26(2):138-54.
[3] Garay-Rondero CL, Martinez-Flores JL, Smith NR, Morales SOC, Aldrette-Malacara A. Digital supply chain model in Industry 4.0. J Manuf Technol Manag. 2020;31(5):887-933.
[4] Gupta M, Jauhar SK. Digital innovation: an essence for Industry 4.0. Thunderbird Int Bus Rev. 2023;65(3):279-92.
[5] Sureeyatanapas P, Pancharoen D, Saengprachatanarug K. Finding the sweet spot in Industry 4.0 transformation: an exploration of the drivers, challenges and readiness of the Thai sugar industry. Benchmarking an International Journal. 2024;31(10):3965-96.
[6] Zhong R, Xu X, Wang L. Food supply chain management: systems, implementations, and future research. Ind Manag Data Syst. 2017;117:2085-114.
[7] Yang M, Fu M, Zhang Z. The adoption of digital technologies in supply chains: drivers, process and impact. Technol Forecast Soc Change. 2021;169:120795.
[8] Ho WR, Tsolakis N, Dawes T, Dora M, Kumar M. A digital strategy development framework for supply chains. IEEE Trans Eng Manag. 2023;70(7):2493-506.
[9] Ageron B, Bentahar O, Gunasekaran A. Digital supply chain: challenges and future directions. Supply Chain Forum Int J. 2020;21(3):133-8.
[10] He Y, Huang H, Li D, Shi C, Wu SJ. Quality and operations management in food supply chains: a literature review. J Food Qual. 2018;2018(1):1-14.
[11] Rogerson M, Parry GC. Blockchain: case studies in food supply chain visibility. Supply Chain Manag Int J. 2020;25(5):601-14.
[12] Adams D, Donovan J, Topple C. Achieving sustainability in food manufacturing operations and their supply chains: key insights from a systematic literature review. Sustain Prod Consum. 2021;28:1491-9.
[13] Büyüközkan G, Göçer F. Digital supply chain: literature review and a proposed framework for future research. Comput Ind. 2018;97:157-77.
[14] Deepu TS, Ravi V. A review of literature on implementation and operational dimensions of supply chain digitalization: framework development and future research directions. Int J Inf Manag Data Insights. 2023;3(1):100156.
[15] Ardito L, Petruzzelli AM, Panniello U, Garavelli AC. Towards industry 4.0: mapping digital technologies for supply chain management-marketing integration. Bus Process Manag J. 2019;25(2):323-46.
[16] Mihardjo LWW, Sasmoko, Alamsjah F, Elidjen. The influence of digital customer experience and electronic word of mouth on brand image and supply chain sustainable performance. Uncertain Supply Chain Manag. 2019;7:691-702.
[17] Bui MT, Jeng DJF, Ta HH. Accelerating digital supply chain management practices, customer development, and firm performance: organizational culture matters. Contemp Econ. 2024;18(1):40-66.
[18] Martínez-Caro E, Cegarra-Navarro JG, Alfonso-Ruiz FJ. Digital technologies and firm performance: the role of digital organisational culture. Technol Forecast Soc Change. 2020;154:119962.
[19] Gagliardi AR, Festa G, Usai A, Dell'Anno D, Rossi M. The impact of knowledge management on the digital supply chain – a bibliometric literature review. Int J Phys Distrib Logist Manag. 2023;53(5/6):612-27.
[20] Queiroz MM, Wamba SF. The role of digital connectivity in supply chain and logistics systems: a proposed SIMPLE framework. In: Hattingh M, Matthee M, Smuts H, Pappas I, Dwivedi Y, Mäntymäki M, editors. Responsible Design, Implementation and Use of Information and Communication Technology. Lecture Notes in Computer Science. Cham: Springer; 2020. p. 79-88.
[21] Bejlegaard M, Sarivan IM, Waehrens BV. The influence of digital technologies on supply chain coordination strategies. J Glob Oper Strateg Sourc. 2021;14(4):636-58.
[22] Kittipanya-Ngam P, Tan KH. A framework for food supply chain digitalization: lessons from Thailand. Prod Plan Control. 2020;31(2-3):158-72.
[23] Ben-Daya M, Hassini E, Bahroun Z. Internet of things and supply chain management: a literature review. Int J Prod Res. 2019;57(15-16):4719-42.
[24] Ivanov D, Dolgui A, Das A, Sokolov B. Digital supply chain twins: Managing the ripple effect, resilience, and disruption risks by data-driven optimization, simulation, and visibility. In: Ivanov D, Dolgui A, Sokolov B, editors. Handbook of Ripple Effects in the Supply Chain. International Series in Operations Research & Management Science. Cham: Springer; 2019. p. 309-32.
[25] Ukolov VF, Shabunevich OV, Sysoev SV. Adaptation to digitalization in supply chain management. Int J Supply Chain Manag. 2020;9(5):1651-6.
[26] Makris D, Hansen ZNL, Khan O. Adapting to supply chain 4.0: an explorative study of multinational companies. Supply Chain Forum Int J. 2019;20(2):116-31.
[27] Burgos D, Ivanov D. Food retail supply chain resilience and the COVID-19 pandemic: a digital twin-based impact analysis and improvement directions. Transp Res E Logist Transp Rev. 2021;152:102412.
[28] Fatorachian H, Kazemi H. Impact of Industry 4.0 on supply chain performance. Prod Plan Control. 2021;32(1):63-81.
[29] Attaran M. Digital technology enablers and their implications for supply chain management. Supply Chain Forum Int J. 2020;21(3):158-72.
[30] Ben-Daya M, Hassini E, Bahroun Z, Banimfreg BH. The role of internet of things in food supply chain quality management: a review. Qual Manag J. 2021;28(1):17-40.
[31] Zorić N, Marić R, Đurković-Marić T, Vukmirović G. The importance of digitalization for the sustainability of the food supply chain. Sustainability. 2023;15(4):3462.
[32] Ahmadzadeh S, Ajmal T, Ramanathan R, Duan Y. A comprehensive review on food waste reduction based on IoT and big data technologies. Sustainability. 2023;15(4):3482.
[33] Amentae TK, Gebresenbet G. Digitalization and future agro-food supply chain management: a literature-based implications. Sustainability. 2021;13(21):12181.

[34] Abideen AZ, Sundram VPK, Pyeman J, Othman AK, Sorooshian S. Food supply chain transformation through technology and future research directions—a systematic review. Logistics. 2021;5(4):83.
[35] Nosratabadi S, Mosavi A, Lakner Z. Food supply chain and business model innovation. Foods. 2020;9(2):132.
[36] Martinelli EM, Tunisini A. Customer integration into supply chains: literature review and research propositions. J Bus Ind Mark. 2019;34(1):24-38.
[37] Alkahtani M, Khalid QS, Jalees M, Omair M, Hussain G, Pruncu CI. E-Agricultural supply chain management coupled with blockchain effect and cooperative strategies. Sustainability. 2021;13(2):816.
[38] Reinartz W, Wiegand N, Imschloss M. The impact of digital transformation on the retailing value chain. Int J Res Mark. 2019;36(3):350-66.
[39] Frankowska M, Rzeczycki A. Reshaping supply chain collaboration - the role of digital leadership in a networked organization. In: Camarinha-Matos LM, Afsarmanesh H, Ortiz A, editors. Boosting Collaborative Networks 4.0. PRO-VE 2020. IFIP Advances in Information and Communication Technology. Cham: Springer; 2020. p. 353-64.
[40] Shashi, Centobelli P, Cerchione R, Ertz M. Agile supply chain management: where did it come from and where will it go in the era of digital transformation?. Ind Mark Manag. 2020;90:324-45.
[41] Queiroz MM, Pereira SCF, Telles R, Machado MC. Industry 4.0 and digital supply chain capabilities. Benchmarking Int J. 2021;28(5):1761-82.
[42] Irfan M, Wang M. Data-driven capabilities, supply chain integration and competitive performance. British Food J. 2019;121(11):2708-29.
[43] Pacolli M. Importance of change management in digital transformation sustainability. IFAC-Pap. 2022;55(39):276-80.
[44] Scholten K, Schilder S. The role of collaboration in supply chain resilience. Supply Chain Manag Int J. 2015;20(4):471-84.
[45] Schwer K, Hitz C. Designing organizational structure in the age of digitization. J East Eur Cent Asian Res. 2018;5(1):1-11.
[46] Wang S, Ghadge A, Aktas E. Digital transformation in food supply chains: an implementation framework. Supply Chain Manag. 2024;29(2):328-50.
[47] Liu Y, Eckert CM, Earl C. A review of fuzzy AHP methods for decision-making with subjective judgements. Expert Syst Appl. 2020;161:113738.
[48] Zhü K. Fuzzy analytic hierarchy process: fallacy of the popular methods. Eur J Oper Res. 2014;236(1):209-17.
[49] Marhavilas PK, Tegas MG, Koulinas GK, Koulouriotis DE. A joint stochastic/deterministic process with multi-objective decision making risk-assessment framework for sustainable constructions engineering projects—a case study. Sustainability. 2020;12(10):4280.
[50] Kharat MG, Murthy S, Kamble SJ, Raut RD, Kamble SS, Kharat MG. Fuzzy multi-criteria decision analysis for environmentally conscious solid waste treatment and disposal technology selection. Technol Soc. 2019;57:20-9.
[51] Rouhani S, Ravasan AZ. A practical framework for assessing business intelligence competencies of enterprise systems using fuzzy ANP approach. Int J Appl Decis Sci. 2015;8(1):52-82.