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Enhancing resilience and reducing waste in food supply chains: a systematic review and future directions leveraging emerging technologies

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ABSTRACT

The sustainability of food supply chains is gaining increasing attention, particularly after the COVID-19 pandemic. A food supply system that simultaneously prioritises resilience and minimises wastage is crucial. It is found that many studies have explored reducing food waste and increasing supply chain resilience as separate objectives, but research is scarce investigating both objectives in conjunction. This paper presents a comprehensive systematic review focusing on existing solutions to reducing food waste and enhancing resilience. It discusses future directions, particularly leveraging emerging technologies such as the Internet of Things, blockchain, artificial intelligence, and machine learning. The studies are categorised into three main topics: crisis resilience solutions, food waste reduction solutions, and integrated solutions. The literature review reveals a lack of empirical and practical solutions for concurrently improving resilience and decreasing food waste. Further in-depth investigations are necessary to propose practical and integrated approaches that tackle both challenges jointly.

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Food supply chain; resilience; food waste; sustainability; integrated solutions; emerging technologies

1. Introduction

Supply chain management (SCM) involves the efficient coordination and control of the flow of goods and services between various locations, where multiple stakeholders are remotely located and engaged in a lengthy process. A typical supply chain connects raw material suppliers, manufacturers, logistics companies, warehouses, shipments, retailers, and end customers (Sahin and Robinson 2002). This process is always intricate and time-consuming, commencing with sourcing raw materials, which are then supplied to a manufacturer. The manufacturer transforms these materials into the final product, which is subsequently passed on to a distributor. The distributor sells the product to a retailer, who, in turn, offers it to consumers, thus completing the cycle. Consumer demand drives the production of additional raw materials, restarting the cycle (Jespersen and Skjott-Larsen 2005). Figure 1 provides a visual representation of a generic supply chain process.

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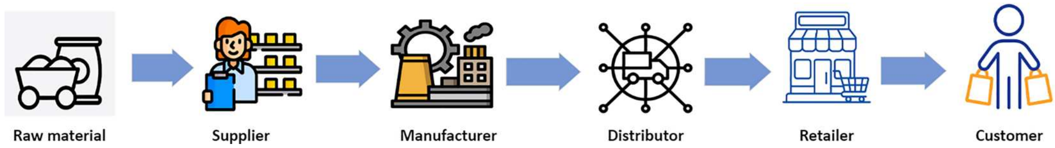

Figure 1. Representation of a generic supply chain.

The supply chain cycle is complex since it usually involves various stakeholders situated in diverse geographical areas. Each involved entity has a specific role in the overall supply chain process. However, each entity maintains its database of resources and prioritises its profits without considering the other stages in the process. Consequently, managing this process with all involved parties poses several challenges, including limited access to data, lack of global collaboration among stakeholders, inadequate resilience capabilities, and significant product waste or shortage (Konstantinos and Michael 2016; Min and Zhou 2002). The use of EDI (electronic data interchange) or application of CPFR (collaborative planning, forecasting and replenishment) between modern supply chain partners have partially addressed some of the problems but their effectiveness and full potential are still affected by many factors, showing a vast disparity among different industries or organisations.

1.1. Background of food supply chain

The Food Supply Chain (FSC), focusing on the movement of food items from farm to consumer, is widely recognised as the most intricate among various supply chain systems due to the perishable characteristics of its products (Shabani, Saen, and Torabipour 2012). Ensuring the timely delivery of food products while maintaining their freshness and quality introduces additional layers of complexity and management challenges across various stages of the FSC, from production, processing, logistics, manufacturing, transportation, distribution, and retail (Manzini and Accorsi 2013). Thus, the FSC and its associated challenges have received significant attention in the literature (Mahajan, Garg, and Sharma 2017; Patidar, Shukla, and Sukhwani 2022; Siddh, Soni, and Jain 2015; Zhong, Xu, and Wang 2017). These challenges encompass inaccurate demand prediction, food waste, poor communication among stakeholders (Mercier et al. 2017), limited resilience, limited system traceability, and data transparency (Astill et al. 2019; Dabbene, Gay, and Tortia 2014; Mustafa and Andreescu 2018; Tsang et al. 2018). Therefore, it is crucial to address the existing challenges to establish more efficient FSC systems, particularly to pay more attention to mitigating food waste as it represents a key metric for achieving sustainability in FSC systems.

Food products are vulnerable to various environmental conditions, which affects the freshness and quality throughout the supply chain, and results in significant food waste. Certain literature studies distinguished between the two terms, food waste and food loss, from multiple perspectives (Chauhan et al. 2021). One dimension focused on the supply chain stage where the waste occurred, including the term food loss referring to wastage within the production, postharvest and processing stages, and the term food waste referring to the wastage at the wholesale, retail and consumption final stages in the FSC (Guarnieri et al. 2021; Porter et al. 2016). Conversely, several studies used both terms interchangeably, referring to the wastage that occurred during any stage along the supply chain (Corrado et al. 2019; Östergren et al. 2014; Parfitt, Barthel, and Macnaughton 2010; Parfitt, Croker, and Brockhaus 2021). Another dimension adopted in literature studies focused on whether the food is edible or inedible. For instance, Redlingshöfer, Coudurier, and Georget (2017) considered food waste and loss the same and used the term food loss as 'food initially produced for human consumption but that was discarded or lost at any stage along the food supply chain'. In this study, we define food waste as the disposal, damage, and spoilage of food products throughout all supply chain stages, including harvesting, post-harvesting, production, storage, processing, distribution, retail, and consumption stages.

It is evident that food waste has become a critical global issue that need to be tackled to achieve sustainability in FSC systems (Kaipia, Dukovska-Popovska, and Loikkanen 2013). Significant efforts have been undertaken to combat this issue, including strategies such as monitoring expiry dates, freshness, and temperature levels, implementing regular shelf-life checks, and ensuring appropriate storage and transportation conditions. Despite these efforts, food waste remains alarmingly high, as evidenced by the Food and Agriculture Organization FAO (2022), which states that 14% of global food is wasted or lost annually during the stages from harvest to the retail market. Furthermore, FAO (2022) also reported that 17% of food waste occurred at the retail and consumer level, contributing to a total of 12% of the world's population facing hunger (Lohnes and Wilson 2018). Considering the projected increase in the global population by 2050 (WRI 2022), providing an adequate food supply poses a significant challenge. Consequently, food waste reduction strategies through the FSC have been incorporated into the 2030 programme for Sustainable Development (FAO 2022).

Simultaneously, developing resilient systems to respond to crises dynamically and adaptively is another crucial aspect of achieving sustainability in FSC systems. Supply chain resilience refers to a supply chain's capacity to respond to interruptions, sustain efficient operations during such disruptions, and swiftly recover to some extent from its initial state (Hohenstein et al. 2015; Ponomarov and Holcomb 2009). The global supply chain disruptions caused by the COVID-19 pandemic have highlighted the vulnerabilities of existing FSC systems and underscored the need for effective strategies to enhance resilience (Gupta et al. 2021; Iftikhar et al. 2024; Modgil et al. 2022; Remko 2020). If a system lacks resilient capabilities to cope with changing conditions, it cannot sustain itself and may result in food waste or shortage. The unexpected closure led to the disposal of large quantities of perishable food items, including fruits, vegetables, meats, and dairy products. Dairy farmers like Darlington Ridge Farms in the US have been forced to discard thousands of gallons of milk daily due to the closure of schools and restaurants during the COVID-19 pandemic (Thornton 2020). One of the UK's largest supermarket chains, Tesco, suffered from disruptions caused by the COVID-19 outbreak, leading to empty shelves and shortage of essential products (AFP 2021). The Food and Agriculture Organization (FAO) has proposed key recommendations to strengthen food system resilience and effectively tackle disruptions (FAO 2020).

Moreover, reducing food waste and enhancing FSC resilience are highly interconnected, with each one influencing and contributing to the other's impact. Building resilient systems that are flexible and proactive ensures that preventative measurements are taken in the run time to mitigate disruption before it occurs. This would contribute to the reduction of food waste. For instance, proactive systems will alert the decision makers to take the timely decision that would minimise the amount of food waste when supply exceeds demand. Additionally, adopting approaches for reducing food waste, would result in building resilient systems as well (Abu Nahleh et al. 2023).

Proposing effective solutions to tackling the intersection of food waste and FSC resilience ensures the sustainability of FSC systems. Within the context of this study, the term 'solution' refers to the various methods that were proposed in the literature for addressing food waste, FSC resilience or the intersection of both. These methods include conceptual frameworks, qualitative studies, quantitative studies, theoretical frameworks, review studies, and mathematical and simulation modelling.

1.2. Impact of emerging technologies on the food supply chain

Among studies that proposed solutions to reducing food waste and enhancing resilience in the FSC, emerging technologies proved effectiveness in developing adaptive systems in the FSC. Emerging technologies such as artificial intelligence (AI), machine learning (ML), blockchain, Internet-of-Things (IoT), digital twin (DT), and data analytics play significant roles in addressing the various challenges faced by different supply chain systems (Aamer et al. 2021; Antonucci et al. 2019; Aramyan et al. 2021; Haji et al. 2020).

IoT connects physical objects to build a network of 'things', such as buildings, vehicles, machines, food products, wearable accessories and home appliances. The physical objects are embedded with electronics, software, sensors, and network connectivity, enabling them to collect data, sense their surroundings, observe parameters like temperature and humidity, and communicate the collected data through the internet for further analysis and real-time decision-making (Atzori, Iera, and Morabito 2010; Díaz, Martín, and Rubio 2016). IoT is considered as a promising technology that enhances the quality of life and reduces human efforts. It has been widely applied in different fields such as smart city, manufacturing, healthcare, and supply chain. In SCM, IoT has received more attention than other technologies since it enables the integration of sensors, data collection devices, and communication systems to gather real-time data on various parameters of perishable products such as temperature, humidity, and gas concentrations (Abideen et al. 2021). Leveraging IoT devices would enable stakeholders to continuously observe the quality progression of perishable products along all supply chain stages and promptly respond to any potential issues (Birkel and Hartmann 2020; Kamble et al. 2019).

Blockchain is a distributed, secure, immutable, and transparent ledger based on a peer-to-peer decentralised network. It consists of blocks that are securely linked to each other, with each block containing time-stamped records of transactions between nodes in the chain, along with the cryptographic hash function of the previous block. Once added to the ledger, the blocks cannot be modified. Blockchain relies on a reliable, transparent, and scalable peer-to-peer network (Mohanta et al. 2019). Integrating blockchain into supply chain systems enables the maintenance of all information, updates, status, and transactions in a shared immutable ledger accessible to all stakeholders, thereby achieving data transparency (Lohmer, Bugert, and Lasch 2020). AI focuses on creating intelligent models that have the capabilities to perform tasks that typically require human intelligence, such as planning, interacting with the real world, reasoning, decision-making, learning, and adapting. ML, a branch of AI, enables models to learn from data and adapt accordingly. ML primarily involves developing computer programmes that can access, use, train, and adapt to data. ML can play a significant role in enhancing various aspects of the supply chain systems, resulting in more improved efficiency, reduced waste, and better decision-making. Many studies emphasised the importance of applying ML algorithms to address various supply chain challenges, such as food product classification, data processing, prediction, and automated decision-making (Baryannis et al. 2019b; Modgil et al. 2022). The Digital Twin (DT) technology refers to the creation of a virtual replica of a physical object, system, or process. This virtual representation simulates the real-world counterpart by replicating its characteristics, behaviour, and interactions. It is created by integrating real-time data from sensors, devices, and other inputs to build an accurate and dynamic digital model (Kamble et al. 2022). In SCM, it refers to the process of creating a virtual representation or replica of a product within the supply chain. It facilities the ability to monitor, simulate, and predict the physical product's behaviour, enabling stakeholders to take proactive actions to improve efficiency and enhance decision-making within a supply chain (Defraeye et al. 2021).

1.2.1. Adoption of emerging technologies for resilience enhancement

Information technology plays a crucial role in enabling resilience in FSC systems. For instance, Lezoche et al. (2020) argued that technological tools significantly contribute to addressing uncertainty by facilitating real-time data sharing among stakeholders. Remko (2020) and Michel-Villarreal et al. (2021) emphasised that technology acted as a catalyst to enhance resilience in the supply chain through supporting collaboration, visibility, and information sharing. Additionally, AI and ML algorithms have immense potential to improve supply chain resilience by monitoring and predicting data trends, enhancing data processing capabilities, and improving decision-making strategies (Cavalcante et al., 2019; Gupta et al. 2021; Naz et al., 2022; Modgil et al. 2022). Recently, there has been a growing interest in adopting AI and ML models to safeguard supply chain systems from disruptions, leading to improved resilience. Utilising ML models for forecasting purposes presents a potential opportunity to develop proactive systems capable of mitigating the impact of disruptions (Abideen et al. 2021; Baryannis, Dani, and Antoniou 2019a). Leveraging advanced ML algorithms with predictive capabilities would build proactive systems that can anticipate potential disruptions and take preventative measures to minimise their adverse effects. IoT devices, such as RFID and sensors, can be utilised to track products, collect real-time data, process data, and provide managers with the necessary information for efficient and effective decision-making (Birkel and Hartmann 2020). Al-Talib et al. (2020) argued that the adoption of IoT devices contributed to improving supply chain resilience by ensuring visibility, information sharing, and collaboration among all stakeholders. Meanwhile, the incorporation of blockchain can also enhance the resilience of supply chain systems by establishing transparency through the consolidation of data within a distributed ledger (Lohmer, Bugert, and Lasch 2020).

Although numerous studies have advocated for utilising emerging technologies to develop resilient and robust systems that address the unique characteristics of FSC systems (Zhong, Xu, and Wang 2017; Tsang et al. 2018; Antonucci et al. 2019; Remko 2020; Sharma et al., 2020; Iftikhar et al. 2024; Modgil et al. 2022; Patidar, Shukla, and Sukhwani 2022), most of these studies are either review and discussion papers or still in the early stages of theoretical conceptualisation and modelling, lacking implementation or testing based on real-life case studies. Further in-depth research is needed to bridge this gap and develop practical and technology-based solutions to enhance resilience in the FSC. Furthermore, despite the increasing interest in adopting IoT, few research solutions have validated its effectiveness in improving supply chain resilience. Al-Talib et al. (2020) noted that only 11% of supply chain-related articles focused on IoT. More investigation is needed to explore and test the capabilities of IoT technology in enhancing supply chain resilience. Moreover, most AI-based solutions (as shown in Table 2) were predominantly conceptual frameworks and primarily qualitative approaches. More research should be conducted to propose empirical and analytical studies to validate the effectiveness of these approaches.

1.2.2. Adoption of emerging technologies for waste reduction

The feasibility of adopting emerging technologies in the FSC to reduce food waste has been emphasised in various literature studies. Canali et al. (2017) argued that technology adoption could effectively address issues such as food perishability, freshness level, and accurate forecasting, thereby reducing food waste. For example, AI and ML algorithms enabled the development of prediction models for perishable products' shelf-life (Hertog et al. 2014). IoT could play a crucial role in monitoring and tracking product quality and temperature along supply chains, thereby minimising waste (Kamble et al. 2019). Blockchain, as highlighted by Li, Lee, and Gharehgozli (2021), facilitated real-time information sharing among stakeholders, which could meet supply with demand and reduce food waste. Despite the importance of the adoption of blockchain to reduce food waste, the integration of blockchain technology into the FSC was primarily associated with enhancing transparency and traceability to ensure food safety (Menon and Jain 2021). Kayikci et al. (2022) conducted semi-structured interviews with managers and professionals representing different entities in Turkish and Indian FSC systems to investigate opportunities of leveraging blockchain technologies into food systems. The adoption of blockchain in the FSC focused on enhancing food safety and security, and utilising blockchain for mitigating food waste presented significant challenges. While a significant number of studies have explored food waste reduction by adopting emerging technologies, it has received comparatively less attention compared to other challenges such as traceability and tracking. It is evident that traceability emerged as the most prominent concept addressed by emerging technologies within FSC systems (Amentae and Gebresenbet 2021). Moreover, it was noted that the integration of blockchain with IoT raised as the leading technology in achieving the objective of traceability along the FSC. Further exploring the role of emerging technologies in mitigating food waste could lead to significant improvements in sustainability and efficiency within the FSC.

Despite the effectiveness of leveraging emerging technologies, adopting them in complex supply chain systems still faces various challenges. Aamer et al. (2021) identified and categorised these challenges into technical, financial, social, operational, educational, and governmental factors in

FSC systems. Aramyan et al. (2021) reviewed various drivers and barriers to adopting innovations for controlling food waste along the FSC. They emphasised the need for managers to conduct feasibility studies before implementing technological tools despite the significant role of innovations in reducing food waste.

Developing adaptive systems that are resilient to crisis while simultaneously reducing food waste is a crucial endeavour for achieving sustainability in the FSC. Despite the growing number of review articles in the field of FSC, most studies paid attention to either food waste or crisis resilience separately, as summarised in Table 1. To the best of our knowledge, there is a lack of integrated solutions in the existing literature that simultaneously address the aspects of food waste and crisis resilience. Therefore, this paper contributes to the field by conducting a systematic review of relevant studies with a focus on the existing solutions to reducing food waste and enhancing resilience either separately or jointly in the FSC.

The main contributions of this paper are threefold. (1) This paper conducts a comprehensive review and analysis of the existing studies on either reducing food waste or enhancing resilience in the FSC from multiple perspectives, spanning research focus, research scope, methodology, and emerging technology adoption. Through this review, it is expected to understand the current state of research and identify the remaining research gaps in this area. (2) Limited studies have investigated the intersection of food waste reduction and resilience enhancement in the FSC. However, the outbreak of COVID-19 and its impact have called for more attention to addressing these two challenges simultaneously. To provide a rigorous review and promote more integrated studies on food waste reduction and resilience enhancement simultaneously in the FSC, this paper conducts a comprehensive survey of the existing studies to suggest a proper focus on future work. (3) Emerging technologies have been increasingly adopted in supply chain management. However,

Table 1. Summary of recent review articles.

	Area of Study					
Reference	Generic	Food waste	Crisis resilience	Food waste and resilience	No. of reviewed articles	Journal
Shashi et al. (2018)	✓				89	The International Journal of Logistics Management
Ali and Gölgeci (2019)			✓		155	International Journal of Physical Distribution & Logistics Management
Golan, Jernegan, and Linkov (2020)			✓		94	Environment Systems and Decisions
de Moraes et al. (2020)		✓			54	Journal of Cleaner Production
Rha (2020)			✓		825	Sustainability
Guarnieri et al. (2021)		✓			29	Logistics
Chauhan et al. (2021)		✓			152	Journal of Cleaner Production
Aamer et al. (2021)	✓				72	Benchmarking: An International Journal
Amentae and Gebresenbet (2021)	✓				76	Sustainability
Abideen et al. (2021)	✓				112	Logistics
Patidar, Shukla, and Sukhwani (2022)	✓				281	Journal of Advances in Management Research
Perdana et al. (2022)			✓		122	International Journal of Disaster Risk Reduction
Yadav et al. (2022)	✓				108	Sustainable Production and Consumption
Iftikhar et al. (2024)			✓		262	Annals of Operations Research
Bayir et al. (2022)	✓				44	Sustainability
Oliveira et al. (2023)			✓		110	The International Journal of Logistics Management
This paper		✓	✓	✓	66	

there is a dearth of relevant reviews on applying various emerging technologies to FSC with a focus on waste reduction and resilience enhancement. This paper particularly pays attention to the existing solutions employing emerging technologies to FSC and recommends more potential applications of emerging technologies to help reduce food waste and improve resilience.

The remainder of this paper is structured as follows: Section 2 outlines the review methodology employed in this study. Section 3 examines the existing solutions to enhancing supply chain resilience, while Section 4 presents the solutions pertaining to food waste. The integrated solutions that have concurrently addressed both resilience and food waste are investigated in Section 5. Subsequently, in Section 6, general discussions from different aspects are conducted, and future research directions are suggested. Finally, Section 7 presents the conclusions.

2. Review methodology

2.1. Literature search

This study employs a systematic literature review approach following the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (McInnes et al. 2018). The literature search process, as outlined in Figure 2, consists of five steps, including formulating research questions, defining keywords, selecting databases, identifying inclusion and exclusion

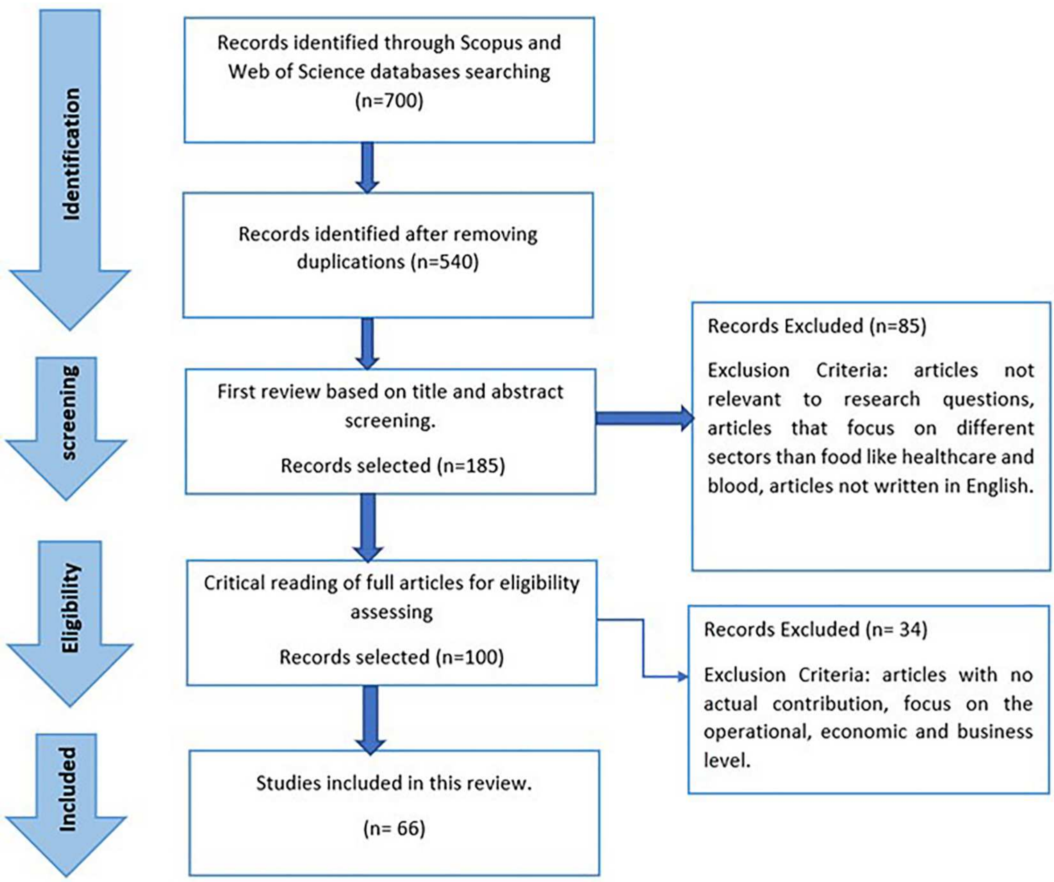

Figure 2. The literature search criteria and process.

criteria, selecting articles, and conducting a comprehensive and critical analysis of the included studies. This study aims to review the existing solutions to addressing food waste and resilience in supply chain systems. To achieve this, the following research questions are formulated and addressed:

(1) What are the existing solutions and challenges to supply chain resilience?
(2) What are the existing solutions and challenges to food waste reduction?
(3) What are the existing solutions to addressing the intersection of food waste reduction and supply chain resilience, and the related challenges?
(4) What are the future research directions based on the identified research gaps and challenges in enhancing resilience and reducing waste in food supply chains?

The first two questions aim to investigate the existing solutions and challenges to supply chain resilience and food waste reduction, respectively. The third question explores the joint problem of supply chain resilience and food waste reduction, while the last question suggests the future research directions to address the joint problem raised in the third question. To answer these research questions, a thorough literature review was conducted by searching the Scopus and Web of Science databases. The search focused on the peer-reviewed articles published in English between the years 2015 and 2023. A combination of relevant keywords was utilised and used to select relevant articles from the identified databases. The keywords included *supply chain, food supply chain combined with the following keywords: challenges, fresh, perishable, waste, wastage, reduction, resilience, resilient, dynamic, adaptive, flexible, robust, disruption, technology, emerging technology, IoT, Internet of things, AI, artificial intelligence, resilience and waste, and loss*. Based on the predefined inclusion and exclusion criteria, 66 articles were selected for inclusion in this review, as illustrated in Figure 2.

2.2. Review process

This paper categorises the relevant articles into three research themes: (1) crisis resilience solutions (41% of the articles) are examined in Section 3, (2) food waste reduction solutions (50% of the articles) are discussed in Section 4, and (3) integrated solutions addressing both resilience and food waste (9% of the articles) are presented in Section 5. Each section provides an in-depth analysis of the relevant articles within its respective category. Furthermore, in Section 6, we conduct a comprehensive analysis and comparison of research studies across all three categories. This analysis enables us to identify current research gaps and explore future research directions, particularly focusing on the leverage of emerging technologies.

3. Solutions for supply chains resilience

Modern supply chain systems operate within a complex and extensive network of stakeholders who must collaborate to ensure the timely delivery of products while maintaining the products' quality and satisfying customers' demands. The inherent complexity of these systems has introduced numerous challenges and vulnerabilities, rendering supply chains susceptible to disruptions, risks, and uncertainties at various stages. Consequently, establishing resilient supply chains that can dynamically adapt to crises has emerged as a competitive advantage in the marketplace. It is worth noting that many existing supply chain systems were designed without considering the dynamic market changes, rendering them more susceptible to disruptions and making it challenging to achieve adaptability and resilience in their operations (Chunsheng et al. 2020; Zouari, Ruel, and Viale 2021). For instance, the COVID-19 pandemic has led to the disruptions of numerous supply chain activities due to unexpected changes, including border closures, demand, and supply uncertainties, shifting customer demands, and raw material shortages (Chowdhury et al. 2020; Taqi et al. 2020). These changes have exposed the weaknesses of existing supply chain systems and underscored the need for designing more robust, sustainable, and resilient supply chain systems that are capable of tackling disruptions dynamically and effectively. Remko (2020) highlighted that around 86% of supply chain systems were negatively affected during the COVID-19 pandemic. Furthermore, the food sector emerged as one of the most affected areas after healthcare, suffering from the disruptions caused by the COVID-19 pandemic (Swanson and Santamaria 2021). These vulnerability stems primarily from the lack of resilient systems capable of effectively navigating disruptions. Consequently, the focus on developing resilient supply chains has intensified, particularly in light of the COVID-19 pandemic (Modgil et al. 2022; Remko 2020). Ali, Mahfouz and Arisha (2017) conducted a literature review to examine the essential elements for enhancing resilience in supply chain systems, while Ali and Gölgeci (2019) identified various barriers and drivers on developing resilient supply chain systems. The literature studies on supply chain resilience have been investigated by a number of review studies (Iftikhar, Purvis, and Giannoccaro 2021; Xu et al. 2020).

Researchers have employed various approaches for strengthening supply chain resilience. Figure 3 categorises the relevant articles based on the research methods adopted to address resilience, including mathematical modelling (35%), simulation models (13%), qualitative studies (9%), conceptual frameworks (17%), and review studies (26%).

Mathematical optimisation models, such as linear programming, Bayesian network modelling, dynamic programming, multi-objective programming, Markov chain processes, and multi-criteria decision-making, are commonly utilised to investigate supply chain resilience (Hosseini, Ivanov, and Dolgui 2019). For instance, Margolis et al. (2018) formulated a multi-objective deterministic optimisation model, considering cost and network connectivity as two objectives, to enhance supply chain resilience from the perspective of network design decisions within a post-acquisition environment. The model was implemented in an industrial case study, demonstrating its effectiveness in reducing costs and maximising connectivity during disruptions. Bottani et al. (2019) developed a non-linear mixed-integer programming model with dual objectives (i.e. maximising profit and minimising total lead time) to measure and enhance resilience in FSC systems. Their formulation

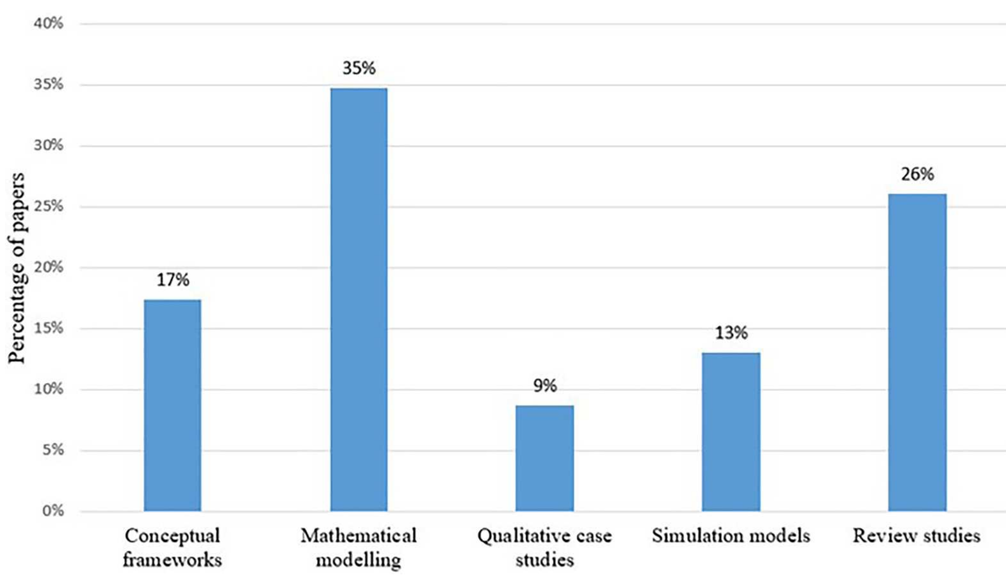

Figure 3. Classifications of resilience studies based on their research methodologies.

was implemented as an Ant Colony Optimization (ACO) algorithm to construct a resilient FSC capable of selecting alternative raw material suppliers under demand uncertainty and optimising time and profits. The ACO algorithm was tested on MATLAB and assessed using a case study involving tomato sauce, demonstrating its effectiveness in operating amid demand fluctuations and raw material disruptions. Furthermore, a mixed-integer stochastic linear programming model was developed by Dutta and Shrivastava (2020) to optimise costs and design resilient supply chain networks that considered uncertainties in demand, supply, and process. The model employed a scenario-based modelling approach to examine and capture random disruptions occurring at manufacturing processing units and transportation routes within the Indian milk supply chain. The outcomes based on sensitivity analysis revealed that the lowest cost was observed in the normal situation when no disruptions were detected. The results further demonstrated that both disruption scenarios (i.e. transportation routes disruption and facilities disruption) resulted in increased costs by 6% and 1%, respectively. Sadrabadi, Jafari-Nodoushan, and Bozorgi-Amiri (2021) proposed a bi-objective stochastic programming model to develop resilient supply chain systems by simultaneously minimising costs and non-resiliency within the network. The mathematical model proposed solutions for both partial and complete disruptions in facilities and transportation links. Effective routing decisions were made to mitigate potential risks arising from these disruptions. The solution was validated by applying three random numerical examples using a CPLEX solver. The results revealed that although the proposed risks resulted in higher costs in the short term, this approach was found to be more profitable in the long term. Sadeghi et al. (2021) devised a robust stochastic programming model that employed redundancy methods to handle disruption scenarios in disasters. The model's performance was assessed by evaluating its behaviour under both normal and disrupted conditions using numerical examples in GAMS software, revealing that the minimal cost was only achieved in normal conditions. Moreover, the proposed model relied on random and small-scale numbers, rendering it unreliable for evaluation in real-life disruptions where most parameters were uncertain. Additionally, Mostaghim, Gholamian, and Arabi (2024) formulated a mixed integer linear programming (MILP) with bi-objectives, minimising carbon dioxide (CO_2) emissions from transportation and maximising overall supply chain profit, to enhance the resilience of the broiler supply chain. The model was solved by utilising goal programming and ε-constraint methods, and was tested on a chicken meat supply chain. Sensitivity analysis revealed the effectiveness of this model to achieve a balanced approach to conflicting objectives.

Selecting the most suitable suppliers under uncertainties and disruptions is important in resilience solutions. Multi-Criteria Decision-Making (MCDM) methods, such as Analytical Hierarchy Process (AHP), Decision-Making Trial and Evaluation Laboratory (DEMATEL), Best-Worst Method (BWM), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), Multi-Attribute Rating Comparison Method for Complex Systems (MARCOS), Stepwise Weight Assessment Ratio Analysis (SWARA), Operational Competitiveness Rating (OCRA), and Multi-Attributive Border Approximation area Comparison (MABAC), are commonly utilised to achieve this objective. For instance, Mohammed et al. (2021) developed a supplier selection model utilising MABAC, OCRA, TOPSIS, and VIKOR MCDM methods to enhance the resilient capabilities of supply chain systems. However, these approaches were time-consuming and highly reliant on predefined factors in the system. Moreover, these models usually overlooked other types of disruptions, such as transportation delays and demand uncertainty. Despite the effectiveness and popularity of MCDM approaches, limited work has been conducted specifically applying these methods in FSC systems. For example, Yazdani et al. (2022) proposed a fuzzy MCDM decision-making model to measure and evaluate resilience in FSC systems. A combination of BWM and MARCOS methods was adopted to identify key risk factors and to assess the resilience of different stakeholders in the FSC under various disruption and risk scenarios. The proposed model was assessed by sensitivity analysis based on a real-life case study. The findings revealed that supermarket retailers and wholesalers' entities presented a high level of stability and resilient capabilities when facing disruptions.

Furthermore, natural disasters were rated as the most significant among various identified risk factors, while excessive inventory was found to be the least critical.

Information technology plays a vital role in enhancing resilience in the FSC, and a recent research stream has emerged focusing on adopting emerging technologies such as artificial intelligence (AI), machine learning (ML), blockchain, Internet of Things (IoT), digital twin (DT) and data analytics (Ali and Aboelmaged 2022; Birkel and Hartmann 2020; Nayal et al. 2021). Gupta et al. (2021) conducted semi-structured interviews with various stakeholders in the field of SCM. The gathered data was examined and utilised to develop an AI-based conceptual framework, which aimed to enable firms to promptly react to disruptions and achieve operational resilience within their supply chains. Similarly, the potential benefits of adopting AI and ML algorithms in building resilient systems were explored through a qualitative approach by Modgil et al. (2022). Semi-structured interviews were conducted with professionals representing various entities within the supply chain to gain deeper insights into the role that AI plays in enhancing supply chain resilience, especially during the COVID-19 pandemic. Based on the data collected from the 31 respondents, a four-stage AI conceptual approach was proposed to enhance resilience in supply chain operations, including risk sensing, risk analysis, network reconfiguration, and rule activation. However, both studies were conceptual models and required empirical testing and implementation to validate their effectiveness. Michel-Villarreal et al. (2021) adopted semi-structured interviews in two case studies to explore the technology capabilities in improving resilient capabilities in short FSC systems. Their findings emphasised the significance of utilising various inexpensive technological tools such as video conferencing, Excel, social media, and WhatsApp to support various resilience capabilities in short FSC systems. Burgos and Ivanov (2021) studied and analyzed the effects of the COVID-19 pandemic on the resilience of a specific food retail supply chain in Germany. The DT technology was applied in anyLogistix software to develop a discrete-event simulation model. Various simulations with different disruption scenarios were conducted to analyze the pandemic's impact on supply chain performance, including surges in demand, supplier shutdowns, and transportation route disruptions. The findings revealed that both demand growth and supplier shutdowns were the most disruptive factors while transportation disruption had a comparatively lower negative impact on the overall supply chain performance. Additionally, the study emphasised the significance of leveraging the DT technology to achieve high visibility within the supply chain, which resulted in more enhanced supply chain resilience. Moreover, Suali, Srai, and Tsolakis (2024) employed a qualitative study to examine the role of adopting digital platforms in enhancing the resilience of e-commerce FSCs under disruptions. A multiple case study approach was adopted through conducting semi-structured interviews with 7 experts from the UK food sector. The Gioia method was applied to extract key concepts from interview data, followed by applying thematic analysis to identify significant themes and valuable insights. Results emphasised on the significant role of digitalisation in establishing a resilience food systems. Sutar et al. (2024) conducted a bibliometric analysis and proposed a conceptual framework to assess factors impacting resilience in FSC. The study proposed effective strategies to mitigating and recovering from disruptions, and further highlighted the effective role of adopting digital technologies such as IoT, AI, ML and blockchain in enhancing resilience in food systems.

Simulation techniques were employed in the literature to enhance supply chain resilience. By utilising simulation, the behaviour of the supply chain under different disruption scenarios could be analyzed and evaluated. For instance, Zhu and Krikke (2020) employed a system dynamic modelling approach to manage a resilient FSC system consisting of three tiers. Three scenarios causing food shortages at the producer, logistic provider, and retailer entities of a cheese supply chain were considered using the Stella software. Resilience was measured using the logistic speed metric, guiding the sharing of relevant information and decision-making for recovery from disruptions. Their findings suggested that the use of information sharing causing endogenous demand during disruptions should be stopped as it could hinder effective decision-making. Tsiamas and Rahimifard (2021) proposed a conceptual framework for strengthening the resilience of FSC systems, focusing on addressing unanticipated disruptions associated with climate change. Additionally, a decision-making simulation model was proposed to assist stakeholders in mitigating these disruptions effectively. To assess the applicability of the proposed framework, multiple simulation scenarios were conducted using the software WITNESS, utilising a real-life dairy supply chain as a case study. Results showed the benefits of simulation approaches, particularly using What-If analysis, to mitigate disruptions under various scenarios. Mu, van Asselt, and van der Fels-Klerx (2021) proposed a conceptual diagram with three tiers (i.e. resilience specifications, resilience measurement, and resilience improvements) to enhance supply chain resilience towards food safety shocks. The proposed diagram was tested by implementing simulation on a pork supply chain. Results indicated that the proposed approach was valuable for retailers in selecting effective strategies to mitigate shocks related to food safety. However, the proposed approach was tested using random parameter values, which reflected the need for further validation using historical data to get more realistic insights for addressing resilience.

Table 2 provides a summary of the existing solutions for supply chain resilience covering multiple aspects including methodology, relevant stakeholders, reactive/proactive approach, technology used, scope, and main contribution. Table 3 presents detailed information on commonly used mathematical models and software/solvers. Based on the review, several research gaps have been identified below:

(1) Only 14% of the research articles focus on resilience, indicating a need for more solutions addressing resilience in supply chain systems (Al-Talib et al. 2020).
(2) Existing solutions primarily concentrate on mathematical optimisation mechanisms (Pires Ribeiro and Barbosa-Povoa 2018). Further investigation is necessary to explore different methodologies and emerging technologies for improving resilience.
(3) Most studies offer general solutions without considering the unique characteristics of FSC. Future research should focus on developing resilient systems specifically tailored to FSC (Queiroz et al. 2020).
(4) Simulation-based solutions in the literature only represent 13% of the existing solutions (as shown in Figure 3). There is a significant opportunity to utilise simulation studies to test the effectiveness of proposed solutions in handling various disruptions in large-scale case studies.
(5) The majority of optimisation models have been validated using small numerical examples or case studies, which may not accurately reflect their effectiveness in real-life disruptions with more complexity and uncertainty.
(6) While there have been significant efforts in improving resilience through supplier selection criteria under disruptions, there is a need to investigate particular disruption scenarios related to FSC. Moreover, proactive approaches should be explored to ensure the dynamic adaptability of the supply chain to changing conditions, as supplier selection alone is a reactive approach.
(7) It becomes apparent from Table 2 that most solutions utilising emerging technologies were either qualitative studies or conceptual framework. There is a pressing need to implement these approaches and put them into practice in real-life situations. Joshi et al. (2023) further highlighted that the lack of utilising emerging digital solutions is still considered a key barrier to improving the supply chain resilience.

4. Waste reduction in food supply chain

Food waste has emerged as a global issue in both developed and developing countries, making it a critical challenge for future sustainable FSC systems. Extensive research has been conducted to explore approaches for reducing food waste (Chauhan et al. 2021; Gokarn and Kuthambalayan 2017; Göbel et al. 2015; Mithun Ali et al. 2019; Xiong et al. 2019). This section examines the

Table 2. Summary of studies on supply chain resilience.

Reference	Methodology	Supply chain stakeholder	Reactive/ Proactive	Emerging technology adopted	Scope	Contribution
Margolis et al. (2018)	Mathematical model	End-to-end	Reactive	N/A	Food	Developed a multi-objective deterministic model for improving resilience
Bottani et al. (2019)	Mathematical model	Supplier	Reactive	N/A	Food	Developed a non-linear mixed-integer optimisation model
Zhu and Krikke (2020)	Simulation model	Producer, logistic supplier, retailer	Reactive	N/A	Food	Conducted a simulation-based scenario that causes food shortage in the milk supply chain
Dutta and Shrivastava (2020)	Mathematical model	Supplier, manufacturer, retailer	Reactive	N/A	Food	Formulated a mixed-integer stochastic programming model to build resilient systems.
Sadeghi et al. (2021)	Mathematical model	Supplier, manufacturer, distributor	Reactive	N/A	Generic	Proposed a multi-objective optimisation model for building a resilient supply chain.
Burgos and Ivanov (2021)	Simulation model	Supplier, manufacturer, retailer	Reactive	DT	Food	Developed simulation model using digital twin (DT) technology
Sadrabadi, Jafari-Nodoushan, and Bozorgi-Amiri (2021)	Mathematical model	Distributor, transporter	Reactive	N/A	Generic	Developed a stochastic programming model to deal with disruptions.
Mohammed et al. (2021)	Mathematical model	Supplier	Reactive	N/A	Generic	Developed an MCDM framework for selecting suppliers under a disruption scenario.
Mu, van Asselt, and van der Fels-Klerx (2021)	Conceptual framework	Retailer	Reactive	N/A	Food	Developed a conceptual model for defining and measuring resilience in FSC.
Gupta et al. (2021)	Conceptual framework	End-to-end	Reactive	AI	Generic	Conducted an interview to get insight into the role of AI in achieving resilient systems. Developed an AI-based conceptual framework.
Michel-Villarreal et al. (2021)	Qualitative case study	End-to-end	Reactive	N/A	Food	Conducted a case study to investigate the impact of technology on enhancing resilience.
Tsiamas and Rahimifard (2021)	Simulation model	Manufacturer	Reactive	N/A	Food	Proposed simulation-based decision model to improve FSC resilience.
Yazdani et al. (2022)	Mathematical model	End-to-end	Reactive	N/A	Food	Developed a fuzzy MCDM decision-making model to evaluate disruptions in FSC.
Modgil et al. (2022)	Conceptual framework	End-to-end	Proactive	AI	Generic	Developed a conceptual AI-based framework for improving resilience
Mostaghim, Gholamian, and Arabi (2024)	Mathematical model	End-to-end	Reactive	N/A	Food	Formulated a mixed-integer linear programming model to enhance resilience.
Sutar et al. (2024)	Conceptual framework	End-to-end	Proactive	Emerging technologies	Food	Proposed a conceptual framework that includes strategies for mitigating disruptions
Suali, Srai, and Tsolakis (2024)	Qualitative case study	Retailer	Proactive	Digital platforms	Food	Conducted a multiple qualitative case studies to explore the role of digital platforms in enhancing the resilience of FSCs

main causes associated with food waste in the FSC, followed by analyzing the existing solutions for its reduction and the identified research gaps.

4.1. Causes and challenges

Understanding how and where food waste occurs, as well as the different causes contributing to this problem, is essential for designing proper solutions to its reduction (Priefer, Jörissen, and Bräutigam 2016). Several studies have discussed the major causes of food waste in the FSC, referring to the various factors that contribute to the generation of food waste at any stage within the FSC (Canali et al. 2017; de Moraes et al. 2020; Göbel et al. 2015; Magalhães, Ferreira, and Silva 2021; Mesterházy, Oláh, and Popp 2020; Shukla and Jharkharia 2013). For instance, Balaji and Arshinder (2016) proposed a Fuzzy and Total Interpretive Structural Modeling (TISM) approach to identify food waste causes in fruit and vegetable supply chains. The lack of integrated IT systems was identified as the major cause of food waste, including the lack of monitoring and traceable system, poor communication among parties and ineffective demand forecasting. They emphasised the necessity of understanding the interrelationships among causes to reduce food waste effectively. Magalhães, Ferreira, and Silva (2021) also utilised Interpretive Structural Modeling (ISM) to determine the root causes of food waste, including inadequate demand forecasting, inadequate packaging, storage at wrong temperature, short product shelf-life and expired products. The proposed approach enabled the identification and implementation of effective mitigation strategies to address food waste along the FSC systems. Mesterházy, Oláh, and Popp (2020) conducted a review to identify the causes of grain loss along the supply chain. The main factors contributing to food waste, as highlighted by the researchers, included the absence of data sharing among stakeholders and insufficient storage and transportation facilities. Additionally, Liu et al. (2022) conducted semi-structured interviews with different stakeholders from the food industry to study the various causes that lead to food waste. The research findings showed that food waste was significantly influenced by poor storage and transportation conditions and inadequate packaging strategies.

A certain number of studies emphasised the importance of stakeholders' collaboration and information sharing in mitigating food waste. Göbel et al. (2015) conducted interviews with 44 food experts to identify the different factors that lead to food waste at different stages. Their findings revealed that the lack of sharing transparent information and the absence of stakeholders' collaboration were two major causes of food waste. Both causes need to be addressed to ensure developing a sustainable FSC. Another review was conducted by de Moraes et al. (2020) to examine and discuss the causes of food waste in the retail sector, highlighting that the lack of collaboration, information sharing, ineffective demand forecasting, short shelf-life and integrated technological tools as major factors contributing to food waste. Building an end-to-end system encompassing all entities and establishing an efficient information sharing system were identified as critical requirements to mitigate food waste (Kaipia, Dukovska-Popovska, and Loikkanen 2013; Shukla and Jharkharia 2013).

In addition, temperature control was identified as a crucial factor for preserving the perishability of food products during storage and transportation (De Venuto and Mezzina 2018). Zoller et al. (2013) argued that improper temperature configuration for perishable food products accounted for approximately 35% of food waste. Maintaining specific temperature levels for food products throughout storage and transportation was vital to ensure freshness (Bremer 2018). For example, perishable products need to be stored at a proper temperature level to ensure their freshness and quality and avoid any spoiling and damaging. Failure to provide a suitable temperature-controlled environment leads to significantly increased food waste.

The spoilage of perishable food products upon reaching their expiry date is another significant contributor to food waste, and the printed shelf-life information exacerbates this issue. According to Lundén et al. (2014), approximately half of the wasted food can be attributed to the shelf-life and printed expiry dates. To mitigate this problem, effective approaches such as promoting products selling to consumers before they expire should be devised (Heising, Claassen, and Dekker 2017).

Table 3. Mathematical models for supply chain resilience.

Reference	Model	Objectives	Disruption type	Software
Margolis et al. (2018)	Multi-objective deterministic optimisation model	1. Minimise cost 2. Maximise network connectivity.	Network design decisions	Gurobi
Bottani et al. (2019)	Non-linear mixed-integer optimisation model.	1. Maximise profit. 2. Minimise total lead time	Select alternative supplier under raw material disruptions	MATLAB
Dutta and Shrivastava (2020)	Non-linear stochastic mathematical model	1. Minimise cost	Route disruptions and distributor facility disruptions	RISKOptimizer
Sadeghi et al. (2021)	Robust stochastic programming model	1. Minimise costs. 2. Maximise supplier's social scores 3. Maximise supplier's environmental scores.	Supplier disruption in a disaster condition	GAMS
Sadrabadi, Jafari-Nodoushan, and Bozorgi-Amiri (2021)	Bi-objective stochastic programming model	1. Minimise costs 2. Minimise non-resiliency	Routing decisions under facilities and transportation disruptions	CPLEX
Mostaghim, Gholamian, and Arabi (2024)	Bi-objective stochastic programming model	1. Maximise total supply chain profits. 2. Minimise CO2 emissions.	Backup distribution centres and allocation of multiple sourcing.	CPLEX

The absence of comprehensive monitoring and traceable systems that track product quality based on their shelf-life also contributes to food waste. A highly effective approach to prevent spoilage involves distributing food products with shorter shelf-life before those with longer shelf-life. Implementing systems that track and monitor product shelf-life enables the successful execution of this approach (Jedermann et al. 2014). Ensuring adequate food product safety, quality, sustainability, and freshness while striving for customer satisfaction and minimising food losses necessitates comprehensive monitoring by all stakeholders involved in the FSC.

Overall, it can be concluded that the various causes of food waste are interrelated, and pose significant challenges to establishing sustainable food systems. This emphasises the necessity of developing comprehensive solutions that consider addressing most of the causes to reduce waste in the FSC. Table 4 provides a summary of the major causes of food waste documented in the literature.

4.2. Waste reduction solutions

Considerable research has been conducted to address food waste by monitoring product quality and adjusting factors such as expiry dates, shelf-life, and prices accordingly. Göransson, Nilsson, and Jevinger (2018) conducted various quantitative field tests to investigate the correlation between temperature and the shelf-life of fresh products in the FSC. Bluetooth low energy sensors and Radio Frequency Identification (RFID) sensors were used to collect real-time temperature data, which was then utilised in a prediction model to estimate both static and dynamic shelf-life for specific products, such as ham and fish. The findings indicated that access to real-time temperature data could result in notable enhancements in terms of food waste reduction and food safety. However, there is a lack of clear guidelines on how to utilise recorded temperature and predicted shelf-life to manage system alarms effectively and reduce food waste. The results also highlighted critical concerns regarding the safety of food products displayed at retailers and stored under fluctuating temperatures. This situation could affect the product's safety and lead to more waste. Torres-Sánchez et al. (2020) conducted a study to gain a deeper understanding of the negative impact that improper temperature conditions could have on the perishable products' quality. The researchers developed a real-time monitoring system integrated with prediction models to minimise food waste by observing the products' temperature and relating them to their shelf life. Two experiments were conducted to monitor the quality conditions of lettuce during storage and transportation by recording shelf-life estimations under different temperatures. Then, a multiple non-linear regression (MNLR) model was utilised to predict the optimal temperature that would extend the shelf-life. Although their model showed promising results in monitoring shelf-life, it was tested on a specific product and may not yield the same results for different types of food. Nikolicic et al. (2021) proposed a simulation-based model to explore the potential for reducing food waste by enhancing the inventory management system with the aid of RFID technology to enable product tracking and information sharing. Two discrete event simulation models were developed using the software GoldSim to simulate and analyze the products' flow between one producer and one supermarket in a dairy supply chain. The first one was used to model the normal supply chain functionality, while the second one incorporated RFID tags to evaluate the impact of information sharing on reducing food waste. The incorporation of RFID technology in the inventory management process yielded promising results. Simulation results proved that the waste from dairy products was reduced by 29.4% in the supermarket, while the reduction reached 38.5% from the producer end. Additionally, Rodrigues et al. (2024) proposed a solution for food waste reduction by developing a demand forecasting framework leveraging machine learning models, including random forest (RF), long short-term memory (LSTM), light gradient-boosting machine (LightGBM) and neural network (NN). The models helped food catering services to predict food demand accurately, avoiding overproduction or underproduction. To test the applicability of the proposed model, it was tested on real case studies related to three different canteens, and results revealed that both RF and LSTM yielded a 14% to 52% reduction in the quantity of wasted meals.

Table 4. Summary of main causes of food waste.

Food waste causes	Description	References
Lack of cold storage facilities/ storage facilities	Storage facilities that are controlled by temperature equipment are essential in keeping food products, especially fresh items, at a specific temperature level that insures preserving their freshness level. Failing to provide that would result in high waste.	Balaji and Arshinder (2016), Mesterházy, Oláh, and Popp (2020), Magalhães, Ferreira, and Silva (2021), Liu et al. (2022)
Lack of communication among supply chain stakeholders	Proper communication among all parties is crucial for monitoring the fluctuations in supply-demand and responding proactively to any disruption that might occur. This would facilitate taking more informed decisions and implementing preventative measurements to avoid food waste.	Göbel et al. (2015), Balaji and Arshinder (2016), de Moraes et al. (2020), Magalhães, Ferreira, and Silva (2021)
Inadequate demand forecasting	Effective demand forecasting is a major factor in minimising the amount of waste. Through predicting the food demand for the next period based on analyzing pre-defined variables, the intent stakeholders will supply accordingly. This will help in matching supply with demand, leading to more reduced waste.	Balaji and Arshinder (2016), Magalhães, Ferreira, and Silva (2021), de Moraes et al. (2020)
Lack of information sharing	Sharing transparent information among all parties has a significant impact on reducing waste. Sharing information such as products, demand, status, major issues, expected disruption, will allow stakeholders to collaborate accordingly and take proper actions to avoid waste.	Göbel et al. (2015), Mesterházy, Oláh, and Popp (2020), de Moraes et al. (2020), Cattaneo et al. (2021), Magalhães, Ferreira, and Silva (2021)
Lack of traceability systems	Implementing traceable systems enables tracking food items along the whole chain, ensuring full visibility and product safety. This helps all parties to acquire, save and share transparent information about food items. Tracking food products helps further in detecting serious issues and taking measurements to mitigating those issues.	Balaji and Arshinder (2016)
Short shelf-life or expired products	Fresh products with short shelf-life have large waste compared to other products. Implementing effective mechanisms to sell such products before they reach expiry dates would achieve a significant reduction in the wasted amount.	de Moraes et al. (2020), Magalhães, Ferreira, and Silva (2021), Cattaneo et al. (2021)
Shortage of refrigerated carriers/ transportation facilities	Carrying food items in non-refrigerated trucks is a major cause of food waste during the transportation stage. Investing in temperature-controlled carriers is potentially costly, however, this solution safeguards food products at the proper temperature level that ensures their quality and freshness throughout long routes or unforeseen disruption.	Zoller et al. (2013), Balaji and Arshinder (2016), Mesterházy, Oláh, and Popp (2020), de Moraes et al. (2020), Magalhães, Ferreira, and Silva (2021), Liu et al. (2022)
Lack of modern packing design and methods	Saving food items, especially the perishable ones, in a proper packing material is required to preserve their qualities and extend shelf-life, contributing to less waste.	Balaji and Arshinder (2016), de Moraes et al. (2020), Magalhães, Ferreira, and Silva (2021), Liu et al. (2022)
Lack of integrated IT systems	Developing supply chain systems without utilising information technology is a major cause of food waste. Adopting technological solutions facilitates sharing transparent information and building appropriate communication among stakeholders, enabling taking informed decision to avoid waste. Additionally, adopting technological solutions helps to resolve many other causes of food waste, through enabling effective monitoring, automating demand forecasting, sharing transparent information and implementing traceable systems.	Balaji and Arshinder (2016), de Moraes et al. (2020)

Dynamic pricing strategies have also been explored as a means of minimising waste for products approaching the expiry dates. Heising, Claassen, and Dekker (2017) presented a conceptual model that combined intelligent packaging (IP) with a dynamic pricing strategy, assuming sensors attached to food packages would record product quality based on temperature. This data was fed to a dynamic pricing system to lower the prices of products nearing their expiry date. The conceptual model was validated in three different scenarios using the software Xpress-IVE. The results revealed that implementing this strategy would yield a significant impact in reducing food waste. However, it remained conceptual and lacked implementation in real-world testing to provide practical insights into its effectiveness. Buisman, Haijema, and Bloemhof-Ruwaard (2019) developed a model to simulate the impact of dynamic shelf-life (i.e. adjusting shelf-life based on product quality) and discounted prices on fresh meat products at retailers. Different scenarios were simulated and compared to extract insights based on profits, waste, and shortage metrics. The results demonstrated that both dynamic shelf-life and discounting approaches were effective in decreasing food waste at the retailer stage. However, applying a dynamic shelf-life strategy had a greater impact in reducing food waste compared to discounting. The results also concluded that integrating a dynamic shelf-life approach with discounting strategies resulted in less waste, reduced shortage, and increased profits. Ou et al. (2021) proposed a decision-making framework for digital transformation in the food retail sector to prove the feasibility of implementing three promotion plans for fresh foods nearing expiry, focusing on reducing food waste and increasing profits. The simulation was conducted using the software FlexSim with real-world sales data of four food categories (i.e. salad, lunch, sushi hand rolls, and rice balls) from two stores in Taiwan. ML algorithms, such as Support Vector Machine, were utilised in the experiments to predict sales by incorporating external variables into the original dataset, such as weather-related factors. The outcomes showed success in reducing food waste and increasing profits. However, the promotion models were applied uniformly without considering specific requirements for each product. Lin and Januardi (2023) proposed a deterministic two-stage pricing model for the fresh FSC, focusing on waste reduction. The first stage represented a static pricing strategy employed when offering fresh food products, while the second stage demonstrated the utilisation of dynamic pricing strategies to sell the fresh products before they spoil. The model, formulated using vertical Nash and Stackelberg games, was tested through numerical experiments and demonstrated the effectiveness of a two-stage pricing approach in reducing spoiled food waste and achieved more profit than applying a single-stage model.

Another research direction for reducing food waste emphasises the importance of building strong communication channels and sharing data among all supply chain parties. Ghinoi, Silvestri, and Steiner (2020) employed social network analysis to study food waste reduction strategies by analyzing and visualising the relationships among stakeholders using graphs. Specifically, Exponential Random Graph Models (ERGMs) were applied to examine the impact of stakeholder interactions on the development of a new food management system. The results emphasised the significance of stakeholders' collaboration in addressing food waste. Riesenegger and Huebner (2022) conducted a qualitative study to investigate methods for reducing food waste in retail bakery stores. Face-to-face interviews were conducted with seven professionals from the retail sector to gather detailed insights. Subsequently, a thematic content analysis was performed on the interview data. The analysis yielded six measures to minimise perishable food waste, including the implementation of an efficient information system and accurate demand forecasting.

Circular economy models have gained attraction in the literature as a means of managing food waste. For example, Kusumowardani et al. (2022) conducted in-depth qualitative interviews to examine the feasibility of implementing circular economy principles to mitigate food waste at the producer, distributor, and retailer stages of an agri-FSC. Based on the findings, a conceptual framework was proposed that applied circular economy strategies to eliminate food waste. The research findings offered valuable insights on understanding food waste causes and mitigation strategies. Similarly, Kabadurmus et al. (2022) developed a circular FSC network model to manage and reduce food waste at the consumption stage. A mixed-integer linear programming (MILP) model was developed with two objectives, minimising the total cost and maximising the distributed food waste. CPLEX was adopted to solve the model and two real-life case studies were used for model performance evaluation. The results demonstrated the effectiveness of the proposed model in mitigating loss within circular FSC.

Although many research studies acknowledge that food waste can occur at different stages of the FSC, consumers also play a significant role in contributing to food waste (Farr-Wharton, Choi, and Foth 2014). One proposed approach to reducing food waste among consumers is to build collaborative platforms such as food-sharing web applications (Pagani and Pardo 2017). Orgut et al. (2016) investigated the food distribution network of an American food bank with a focus on reducing food waste. The problem was formulated as a deterministic linear programming model to donate food with two objectives: optimising the food bank's performance while satisfying a predefined constraint on the level of inequality among regions. The theoretical optimal solutions had the potential to significantly enhance the equity level while minimising waste. Harvey et al. (2020) applied a social network analysis to an existing mobile sharing application used by users to donate and reuse food items. The software Cephi was utilised to visualise the network graph of the mobile application platform. The results of the analysis demonstrated that using such applications had a substantial impact on reducing food waste. Bilska, Tomaszewska, and Kołożyn-Krajewska (2020) proposed a risk management conceptual model for food waste reduction in the food service and hospitality sector. First, a qualitative approach was employed by conducting surveys and questionnaires with 130 food service companies in Poland. Then, a descriptive statistics analysis was performed on the collected data. The analysis primarily served as the foundation for proposing a risk management conceptual model consisting of four stages: risk identification, risk analysis, risk evaluation, and risk treatment. The proposed model identified the causes of food waste, such as excessive food preparation and inappropriate storage conditions, estimated the risk of food waste at medium or high levels, and suggested preventive measures for reducing food waste in the food service sector.

Qualitative approaches enable researchers to capture and analyze real-life experiences and opinions of individuals and professionals involved in the food industry, providing valuable insights about the practical implications of adopting various solutions to mitigate food waste. Guarnieri et al. (2021) conducted qualitative case studies to identify effective solutions for waste reduction in the distributor and retailer sections of the fruit and vegetable supply chains. Semi-structured interviews were conducted with 19 retailers and eight wholesalers as a part of the research methodology. Following the interviews, a content analysis was performed on the data obtained from these interviews. The results highlighted the importance of facilitating proper storage conditions, influencing customer behaviour, and implementing logistics practices to reduce food waste. Rodrigues et al. (2021) proposed a theoretical framework combining multiple approaches, including a conceptual framework, structured questionnaire, semi-structured interviews, and data analysis, for reducing food waste in online retail. Moreover, Annosi et al. (2021) applied a qualitative approach and conducted in-depth interviews with 18 professionals in the food industry. The main objective was utilising collaborative digital technologies to prevent and reduce food waste. The findings indicated that food waste prevention could be achieved through the integration of digital systems into the entire food system. The researchers argued that food companies should prioritise investments in the adoption of digital tools to help facilitate consistent communication and enable efficient information sharing among all parties involved in the FSC. By embracing digital technologies, companies have opportunities to reduce food waste effectively and enhance collaboration across the entire FSC. Additionally, Winkler, Ostermeier, and Hübner (2023) conducted structured interviews with 13 professionals from the German grocery retail market, including supermarkets, hypermarkets and wholesalers to get insights about the best practices for food waste prevention approaches. Data content analysis was further utilised to provide potential barriers that retailers need to address for mitigating food waste, and to suggest food waste prevention practices. The analysis revealed

Table 5. Summary of studies on food waste reduction.

Reference	Methodology	Stakeholder/ Stage	Emerging technology adopted	Contribution
Göbel et al. (2015)	Qualitative study (Interviews)	End-to-end	NA	Conducted qualitative interviews to determine the causes/effects of Food waste
Orgut et al. (2016)	Mathematical model (Linear programming model)	Distribution	NA	Developed a deterministic optimisation model for distributing the donated food left in the food bank.
Heising, Claassen, and Dekker (2017)	Conceptual model	Production, Retail	Sensors	Developed a conceptual model using intelligent packaging with dynamic pricing to reduce food waste.
Göransson, Nilsson, and Jevinger (2018)	Quantitative case studies (Field tests)	End-to-end	Bluetooth and RFID sensors	Proposed a temperature-based monitoring system to collect temperature data and predict both static and dynamic shelf-life.
Buisman, Haijema, and Bloemhof-Ruwaard (2019)	Simulation model	Retail	NA	Developed an optimisation model to study the impact of a dynamic shelf-life approach on food waste and profit
Torres-Sánchez et al. (2020)	Quantitative case study (Experiments)	Storage and Transportation	Sensors, Machine learning	Developed a monitoring system and non-linear regression model for finding the relation between temperature and shelf-life
Harvey et al. (2020)	Qualitative case study (Social network analysis)	Consumption	NA	Conducted a network analysis on a web application that is designed to share food between customers to reduce waste.
Bilska, Tomaszewska, and Kołożyn-Krajewska (2020)	Conceptual model	Food service	NA	Developed a risk management model for food waste in the food service sector.
Ghinoi, Silvestri, and Steiner (2020)	Quantitative study (Social network analysis)	End-to-End	NA	Applied social network analysis to examine the impact of stakeholder interactions on reducing food waste.
Nikolicic et al. (2021)	Simulation model	Supply, Retail	RFID	Developed a simulation model for minimising food waste by facilitating the sharing of real-time data using RFID tags.
Guarnieri et al. (2021)	Qualitative case study (Semi-structured interviews)	Distribution and Retail	NA	Conducted semi-structured interviews to explore the proper solutions for reducing waste.
Ou et al. (2021)	Simulation model	Retail	Machine learning	Developed a simulation-based decision-making model to reduce food waste and increase profit.
Rodrigues et al. (2021)	Qualitative case study	Supply, Retail and Consumption	NA	Developed a theoretical framework for food waste reduction at an online retailer.
Annosi et al. (2021)	Qualitative case study (Semi-structured interviews)	Production and Retail	NA	Conducted in-depth interviews to gain comprehensive insights into the role of digital technology in food waste reduction.
Kabadurmus et al. (2022)	Mathematical model (Deterministic MILP optimisation model)	Consumption	NA	Developed both a circular FSC network model and a MILP formulation to mathematically represent their model for managing food waste at the consumption stage.
Riesenegger and Huebner (2022)	Qualitative study (Structured interview)	Retail	NA	Conducted a qualitative framework for reducing food waste at the retailer.
			NA	

(*Continued*)

Table 5. Continued.

Reference	Methodology	Stakeholder/ Stage	Emerging technology adopted	Contribution
Kusumowardani et al. (2022)	Qualitative study (Semi-structured interviews)	Production, Distribution and Retail		Proposed a conceptual framework that applies circular economy strategies to eliminate food waste.
Lin and Januardi (2023)	Mathematical model (Deterministic model)	Supply and retail	NA	Formulated a deterministic mathematical two-stage pricing model for perishable FSC to minimise food waste.
Winkler, Ostermeier, and Hübner (2023)	Qualitative study (Structured interview)	Retail	NA	Conducted in-depth interviews to gain insights into the best practices to reduce and prevent food waste
Rodrigues et al. (2024)	Quantitative case study (Experiments)	Food service	Machine learning	Developed a demand forecasting framework leveraging machine learning to reduce waste.

that implementing more advanced automated forecasting is a significant practice in preventing food waste.

Table 5 provides a summary of the existing solutions for food waste reduction. It is evident from Table 5 that most studies focused on some specific stages of the FSC, creating the necessity for more studies that consider solutions covering the whole chain. Additionally, Figure 4 categorises the relevant literature based on the applied methodologies, revealing that food waste has been addressed by applying different methodologies. However, most of them are qualitative studies (36%), and review studies or conceptual frameworks (21%).

5. Integrated solutions for the food supply chain

The existing solutions for FSC resilience and food waste reduction have been reviewed in Section 3 and Section 4, respectively. This section aims to review studies at the intersection of addressing resilience and food waste in the FSC simultaneously.

Limited studies have been conducted on providing comprehensive solutions that simultaneously address food waste reduction and resilience in the FSC. Moraes et al. (2019) conducted a review to

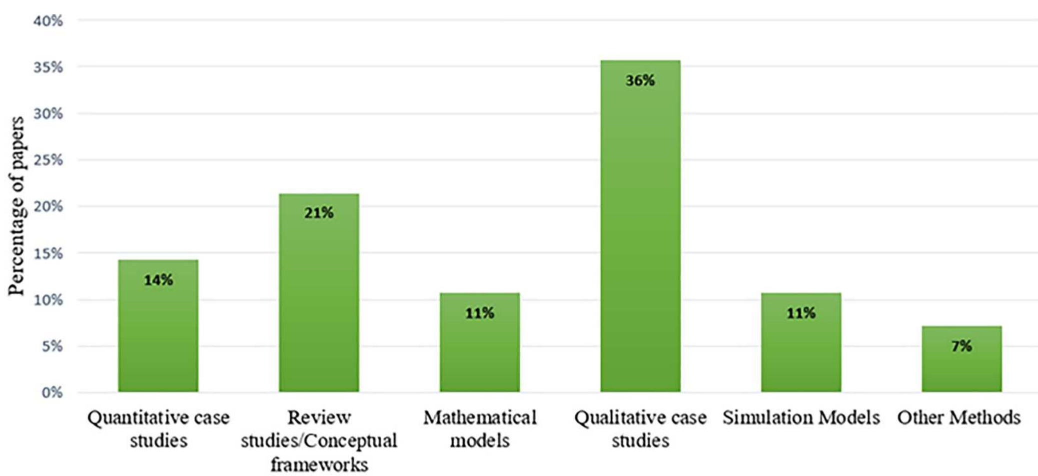

Figure 4. Classification of food waste solutions based on research methodologies.

discuss the connection between food waste causes and resilience elements. The analysis revealed that redundancy and financial strength were potential barriers to reducing the effects of food waste, while collaboration and flexibility demonstrated a positive influence in reducing waste causes. While these studies highlighted the role of resilience in reducing food waste, they primarily provided discussions without proposing practical solutions to address both challenges simultaneously. Mithun Ali et al. (2019) developed an integrated grey-DEMATEL framework that identified the interrelation between risk factors in FSC systems. Surveys and questionnaires were completed by food industry managers and professionals to identify various risks in FSC systems. Subsequently, an integrated framework utilising the Grey System Theory (GST) and the DEMATEL method was employed to identify the interrelationship between different risk factors and the issue of food waste. The proposed solution aimed to enhance risk mitigation and minimise food waste in FSC systems. Bajželj et al. (2020) took a theoretical approach to analyze the relationship between achieving greater resilience and generating less waste in FSC systems from both positive and negative aspects. The analysis results revealed that achieving a significant reduction in food waste was crucial for establishing long-term resilience within FSC systems. However, it is worth noting that such reductions might entail short-term trade-offs. Costa et al. (2022) conducted semi-structured interviews with 47 suppliers and retailers to investigate the correlation between food waste reduction and resilience in a fruit and vegetable retail market in Brazil. Upon analyzing the gathered interview data, the findings revealed that resilience can have a dual role in the context of food waste reduction. Some resilience elements, such as flexibility and communication, helped in food waste reduction, while other elements like redundancy, have the potential to increase food waste. Singh et al. (2023) applied the novel grey causal modelling (GCM) approach to identify the significant of DT in reducing waste and improving resilience of FSCs. Data was collected from experts in the food industry to identify 15 factors affecting resilience of FSC through utilising DT technology. The factors were further analysised through utilising the GCM approach, and results emphazied on the significant impact of adopting DT in increasing visibility and traceability, reducing waste, enhancing resilience and sustainablity. Figure 5 classifies the relevant articles based on the research methodologies employed.

Table 6 summarises the existing solutions that have addressed food waste and resilience in the FSC in an integrated way. Existing studies primarily consist of qualitative discussions and exploratory studies, lacking quantitative and application solutions for effectively addressing these two challenges simultaneously. It is evident that one qualitative study emphasised the potential of utilising DT technology to address food waste and resilience jointly. As far as our knowledge extends, there is no prior

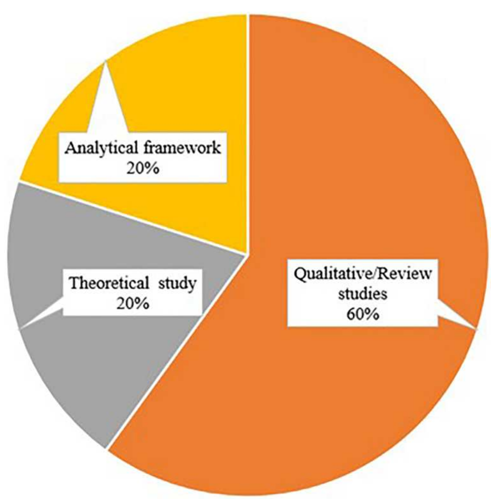

Figure 5. Classification of studies based on research methods.

Table 6. Summary of Integrated Solutions.

Reference	Methodology	Stakeholder/ Stage	Emerging technology adoption	Contribution
Mithun Ali et al. (2019)	Analytical model	Producer	NA	Proposed an integrated grey-DEMATEL framework for identifying the interrelation between risk factors in FSC systems.
Moraes et al. (2019)	Review study	Retailer	NA	Proposed a review to study the relation between food waste causes and resilience.
Bajželj et al. (2020)	Theoretical study	End-to-End	NA	Used a theoretical approach for studying the relationship between food waste and resilience.
Costa et al. (2022)	Qualitative case study	Supplier, Retailer	NA	Conducted a qualitative study to see if resilience contributes to food waste reduction.
Singh et al. (2023)	Qualitative case study	End-to-End	DT	Utilised the GCM approach to identify and analyze the main factors affecting resilience and lead to less waste through applying DT.

quantitative research that has addressed resilience and food waste reduction jointly in FSC systems through the adoption of emerging technologies. Hence, it is necessary to design integrated and technology-based solutions to establish crisis-resilient FSC systems that effectively minimise food waste.

6. Discussion and future research directions

6.1. Discussion

Through a rigorous review and analysis of the existing literature on reducing food waste or enhancing resilience either separately or jointly in the FSC, this study explored the current state of research, identified research gaps and suggested future directions. By investigating the included articles, we addressed the four research questions: (1) What are the existing solutions and challenges to supply chain resilience? (2) What are the existing solutions and challenges to food waste reduction? (3) What are the existing solutions to addressing the intersection of food waste reduction and supply chain resilience, and the related challenges? And (4) What are the future research directions based on the identified research gaps and challenges in enhancing resilience and reducing waste in food supply chains?

To answer the first research question, an in-depth investigation was conducted on the included studies to explore the different solutions proposed for enhancing supply chain resilience in Section 3. Our findings revealed that resilience was mostly addressed by proposing mathematical modelling for generic supply chains without focusing on food requirements. It is worth noting that a significant proportion of existing studies proposed conceptual frameworks without providing evidence of their effectiveness and feasibility. There is an evident lack in the existing literature for solutions that focus on leveraging emerging technologies to enhance resilience.

Section 4 addressed the second research question through investigating the current solutions for reducing food waste. Our results indicated that food waste reduction was addressed through adopting various methods, including qualitative studies, quantitative studies, simulations, mathematical modelling, review studies and conceptual frameworks. Despite much effort, food waste is still increasing and there is a pressing need to propose effective solutions. Studies that addressed the intersection of food waste and resilience (the third research question) were reviewed in Section 5. Results proved that there is an apparent lack in proposing technology-based solutions in the current body of studies for addressing the intersection of food waste and resilience. Evidently, the existing studies proposed theoretical and discussion solutions, lacking the implementation of effective and practical solutions for addressing this issue. Future studies are needed to propose solutions, leveraging emerging technologies, for reducing food waste and enhancing resilience jointly in the FSC.

Table 7. Summary of relevant studies.

Reference	Research focus			Research scope		Methodology	Emerging technology adoption
	Food waste	Crisis resilience	Integrated solutions	Partial FSC	Whole FSC		
Orgut et al. (2016)	✓			Distributor		Mathematical model	No
Heising, Claassen, and Dekker (2017)	✓			Producer, retailer		Conceptual model	Yes
Göransson, Nilsson, and Jevinger (2018)	✓				✓	Case study	Yes
Margolis et al. (2018)		✓			✓	Mathematical model	No
Mithun Ali et al. (2019)			✓	Producer		Analytical Model	No
Buisman, Haijema, and Bloemhof-Ruwaard (2019)	✓			Retailer		Simulation	No
Bottani et al. (2019)		✓		Supplier		Mathematical model	No
Bajželj et al. (2020)			✓		✓	Theoretical study	No
Harvey et al. (2020)	✓			Customer,		Case study	No
Dutta and Shrivastava (2020)		✓		supplier, manufacturer, retailer		Mathematical model	No
Zhu and Krikke (2020)		✓		Producer, supplier, retailer		Simulation	No
Torres-Sánchez et al. (2020)	✓			Storage, Transportation		Case Study	Yes
Bilska, Tomaszewska, and Kołożyn-Krajewska (2020)	✓			Food service		Conceptual model	No
Ghinoi, Silvestri, and Steiner (2020)	✓				✓	Case study	No
Rodrigues et al. (2021)	✓			Supplier, retailer, customer		Case study	No
Mu, van Asselt, and van der Fels-Klerx (2021)		✓		Retailer		Conceptual model	No
Mohammed et al. (2021)		✓		Supplier		Mathematical model	No
Gupta et al. (2021)		✓			✓	Conceptual model	Yes
Sadrabadi, Jafari-Nodoushan, and Bozorgi-Amiri (2021)		✓		Distribution centre, transportation		Mathematical model	No
Ou et al. (2021)	✓			Retailer		Simulation	Yes
Nikolicic et al. (2021)	✓			Supplier, retailer		Simulation	Yes
Michel-Villarreal et al. (2021)		✓			✓	Case study	Yes
Sadeghi et al. (2021)		✓		Supplier, manufacturer, distributor		Mathematical model	No
Guarnieri et al. (2021)	✓			Distributor, retailer		Case study	No
Tsiamas and Rahimifard (2021)		✓		Manufacturer		Simulation	No
Annosi et al. (2021)	✓			Producer, Retailer		Case study	Yes
Burgos and Ivanov (2021)		✓		Supplier, manufacturer, retailer		Simulation	Yes

(*Continued*)

Table 7. Continued.

Reference	Research focus			Research scope		Methodology	Emerging technology adoption
	Food waste	Crisis resilience	Integrated solutions	Partial FSC	Whole FSC		
Yazdani et al. (2022)		✓			✓	Mathematical model	No
Costa et al. (2022)			✓	Supplier, retailer		Qualitative study	No
Modgil et al. (2022)		✓			✓	Conceptual model	Yes
Riesenegger and Huebner (2022)	✓			Retailer		Qualitative study	No
Kusumowardani et al. (2022)	✓			Producer, distributor, retailer		Case study approach	No
Kabadurmus et al. (2022)	✓			Consumption		Mathematical model	No
Lin and Januardi (2023)	✓			Supplier, retailer		Mathematical model	No
Winkler, Ostermeier, and Hübner (2023)	✓			Retailer		Qualitative study	No
Singh et al. (2023)			✓		✓	Qualitative study	Yes
Mostaghim, Gholamian, and Arabi (2024)		✓			✓	Mathematical model	No
Sutar et al. (2024)		✓			✓	Conceptual model	Yes
Rodrigues et al. (2024)	✓			Food service		Case study	Yes
Suali, Srai, and Tsolakis (2024)		✓		Retailer		Qualitative study	Yes

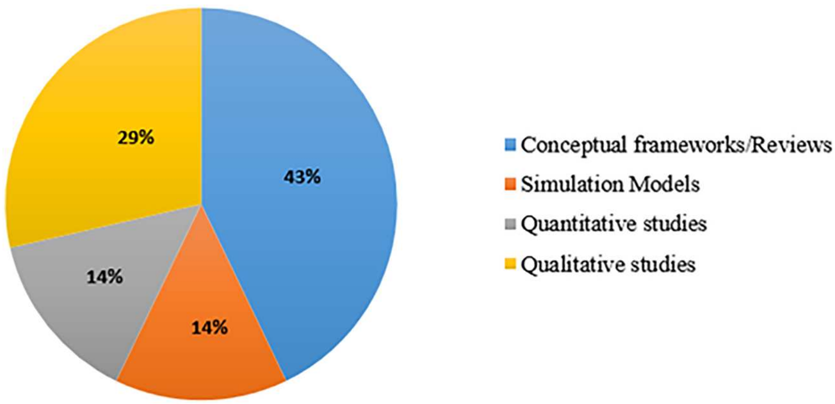

Figure 6. Classification of emerging technological solutions.

Additionally, studies under the three research themes were analyzed from multiple perspectives as shown in Table 7, including research focus (crisis resilience, food waste or integrated solutions), research scope (partial supply chain or whole chain), methodology (conceptual model, mathematical model, case study, simulation and review studies) and emerging technology adoption (incorporating or not). It is noticed that rare work (only 9%) has been done towards proposing integrated solutions for addressing resilience and waste reduction in FSC systems. Our findings revealed that the existing solutions mostly focused on some specific components in the FSC, such as suppliers, manufacturers, distributors, retailers, or customers. Only a few simulation-based models have been used to validate the feasibility of adopting emerging technologies. More investigation is needed to explore the adoption of emerging technologies and test their feasibility through different methodologies.

Figure 6 classifies the literature studies that centre on emerging technologies based on their research methodologies, demonstrating that the most prominent methods adopted in the reviewed articles were conceptual and review studies, accounting for 43% of the total articles analyzed. Qualitative research methods were also employed in 29% of the reviewed articles. These studies involved conducting semi-structured interviews to gain valuable insights into the role of emerging technologies in reducing food waste and enhancing resilience within the FSC. Qualitative approaches facilitate capturing and analyzing real-life experiences and opinions of professionals involved in the industry, providing deeper understanding of the practical implications of adopting digital technologies. The figure highlights a notable lack in the utilisation of emerging technologies in quantitative studies, accounting for 14% of the reviewed articles, and simulation studies, representing 14% of the total. Both methods are essential for validating the effectiveness of emerging technologies in addressing food waste and enhancing resilience in the FSC. Bridging this gap and conducting more quantitative and simulation-based studies would offer more practical applications of technological solutions in the context of the food industry.

By addressing these research gaps, future studies have the potential to contribute significantly to a more comprehensive understanding of resilience enhancement and waste reduction in FSC systems, and provide innovative solutions supported by various methodologies and emerging technologies.

6.2. Future research directions

Based on the comprehensive systematic review and the identified research gaps, multiple future research directions are recommended as follows:

(1) Developing hybrid solutions that combine simulation and optimisation methods holds great potential for managing disruptions in real-life FSC systems where most inputs are unknown (Juan et al. 2018). For instance, food retailers could apply optimisation models to establish resilient systems, incorporating simulation to test the applicability of such systems to handle uncertain situations, including demand fluctuation, extreme weather conditions, crisis and transportation delays. Applying this approach holds a significant promise on building proactive systems that are prepared to effectively handle sudden disruptions, leading to more enhanced resilience.
(2) The combination of blockchain and DT technologies has been utilised and proved its applicability in various applications, including healthcare, smart cities, automobile, manufacturing and smart transportation (Yaqoob et al. 2020). Adopting a similar approach will have a significant impact on the overall performance, security and privacy of the FSC systems. For example, stakeholders could implement an integrated system of blockchain-based DT technology to enhance the system performance during the transportation stage (Sahal et al. 2021). By leveraging both technologies during transportation, stakeholders and decision-makers will attain end-to-end tracking and visibility on products during their movement, enabling them to identify potential risks (i.e. road closure, route failure, products' spoilage), effectively reacting to uncertain disruptions, and taking informed decisions to reduce food waste at real time.
(3) IoT has been widely used for monitoring food products during the storage and transportation stages in the FSC. Subsequent studies should focus on adopting IoT devices at the retail stage to facilitate monitoring the perishability of fresh products while they are positioned on retailers' shelves, considering that these products are highly vulnerable to fluctuated temperature (Göransson, Nilsson, and Jevinger 2018). Food retail companies are highly recommended to deploy IoT devices on the shelves where fresh products (i.e, fruits and vegetables) are usually displayed, enabling retailers to continuously monitor the products' freshness level by collecting real-time temperature data. Furthermore, incorporating this approach with ML predictive models would provide a further significant enhancement in terms of taking preventive measures and making data-driven and real-time action to minimise food waste.
(4) While the leveraging of blockchain technology yields substantial benefits to all of the involved parties in the FSC, a particular focus should be given to the manufacturing and processing centres for amplifying further benefits. For instance, processing centres for fresh fruits and vegetables are highly recommended to track and monitor the conditions of these products during their journey from farms until reaching the processing centres by implementing traceable system utilising blockchain technology (Monica-Paula, Marin, and Vidu 2021). Such traceable systems would provide processing centres with comprehensive insights into the fresh products' status, enabling them to proactively detect any potential risk issues and taking informed actions that would guarantee processing the products while meeting the safety standards.
(5) Utilising the predictive capabilities of ML models through quantitative studies is considered a promising solution to enhancing resilience and reducing food waste in the context of FSC systems. Particularly, food retail companies (i.e. grocery stores, supermarkets) could utilise ML models to forecast the daily demand of highly perishable food products (i.e. fruits, vegetables, dairy products), with a particular focus on incorporating shelf-life information into the proposed model (Priyadarshi et al. 2019). This approach will provide retailers with accurate demand, particularly for fresh products that have short lifetime, and facilitate making informed decisions that would guarantee matching demand with supply, leading to food waste reduction. Additionally, the application of ML models in the distribution and transportation stages presents an open and interesting research direction. Stakeholders involved in the distribution and transportation stages could apply ML models to dynamically predict the road conditions, enabling them to take appropriate routes that would ensure fast delivery of fresh products to retail stores while maintaining their freshness.

(6) Although IoT technology has been widely studied and applied in SCM, the investigation of leveraging IoT with other emerging technologies remains a hot research direction that needs further investigation. For instance, leveraging the integration of IoT and blockchain technologies would facilitate transforming food systems into a more transparent and efficient system. This integration empowers stakeholders, including all relevant parties, with reliable and secure information, leading to increased productivity and more trust. Furthermore, integrating IoT with DT technology holds great potential for enhancing the overall performance and efficiency of the FSC systems (Defraeye et al. 2021). Implementing such approaches would be helpful to enhance the FSC performance in general, including food waste reduction and resilience enhancement.

7. Conclusion

To achieve sustainability in the FSC systems, it is crucial to build resilient systems with minimal food waste. In this study, a comprehensive and systematic review was conducted to gain insights into the current state of research in this field. The review was organised into three themes: (1) solutions for improving resilience, (2) studies on reducing food waste, and (3) integrated solutions addressing both resilience and food waste in the FSC systems. We analyzed and summarised relevant studies from research methodology, research focus, and stakeholder involvement to identify the research gaps and suggest future research directions. Our findings revealed that food waste has received substantial attention in the literature, with various research methodologies employed, including review studies, conceptual frameworks, qualitative and quantitative studies, mathematical and simulation modelling. On the other hand, supply chain resilience has predominantly been addressed through optimisation models. Moreover, rare studies investigated joint solutions of reducing food waste and improving resilience in the FSC systems. It is found that emerging technologies such as IoT, AI, ML, and blockchain possess capabilities that can effectively address various challenges in supply chain management. This indicates a great potential of adopting emerging technologies to reduce food waste and improve resilience in the FSC systems. Therefore, developing technology-based solutions that address food waste reduction and resilience enhancement simultaneously represents a promising research direction and needs further investigation. Although this study conducted an in-depth review of literature studies in this field, it also has some limitations. Firstly, the literature search was limited to the Scopus and Web of Science databases, potentially overlooking relevant articles from other databases. Additionally, our review focused solely on articles published in English, excluding studies in other languages, which may have resulted in the omission of important research.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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