Technological Forecasting & Social Change 217 (2025) 124175

Contents lists available at ScienceDirect

Technological Forecasting & Social Change

journal homepage: www.elsevier.com/locate/techfore

Tackling food waste and loss through digitalization in the food supply chain: A systematic review and framework development

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A R T I C L E I N F O

Keywords:
Digitalization
Digital supply chain integration
Food waste and loss
Food supply chain
Systematic literature review

A B S T R A C T

With growing concern about food security in recent years, the use of digitalization to address food waste and loss (FWL) events has become an increasing focus of academic research. Most current FWL studies however are fragmented and dispersed, focusing only on specific digital technologies applied to the food supply chain (FSC). This study utilizes a systematic literature review (SLR) approach to analyze 4277 abstracts and titles, along with 129 full-text papers on the topic (111 papers finally included) from 2014 to 2024. It provides a unified and comprehensive overview of how state-of-the-art digital technologies are being used to tackle complex FWL events within the FSC. This review identifies and integrates the potential of 16 digital technologies, examining their application methods, the corresponding FWL events and deployment phases within the FSC (i.e. Production, Handling & Storage, Processing & Packaging, Distribution & Retail, and Consumption). Based on the findings of this review, a digital FWL network management framework is developed. This framework describes the relationships among drivers, actors, causes, actions, time, and places involved in addressing FWL, aiming to simulate the real-world process of how digitalization can tackle complex FWL events. Furthermore, this review investigates the research trend, sustainable impact, potential drawbacks, and deployment obstacles of digital technologies in reducing FWL, and subsequently identifies future research directions. Overall, this study adopts a promising multiple-technology perspective to systematically illustrate how different digital technologies can address FWL events at various phases of the FSC.

1. Introduction

Food waste and loss (FWL) has always been an unavoidable challenge in the food supply chain (FSC) field, negatively impacting the environment, economy, and society (Pinto et al., 2022). From an environmental point of view, there is a great deal of land, water, and energy involved in the production of food. FWL not only results in the loss of these resources but also increases environmental pressure. Moreover, the production and processing of food releases many tons of greenhouse gases such as carbon dioxide and methane. Large FWL events are not only the opposite of reducing greenhouse gas emissions, but also contribute to global warming or climate change (Jeswani et al., 2021). The food industry occupies an important position in the global economy - FWL may also lead to the reduction of income of farmers and a downturn in the agricultural economy, affecting the sustainable development process. This further aggravates poverty and hunger in our society, which may give rise to social unrest, inequalities and political crises (Alonso-Fradejas et al., 2015). According to a statistical report from the United Nations Food and Agriculture Organization (FAO, 2013), a third of food produced worldwide is wasted, amounting to over one billion tons - enough to feed 940 million people (Abbade, 2020). Thus, identifying effective strategies to tackle food waste and loss is a topic of significant importance and deserves in-depth exploration.

FWL is a longstanding concern for both academia and society. More recently, the outbreak of Covid-19, which significantly disrupted the FSC and heightened food insecurity issues (Music et al., 2021; Deaton and Deaton, 2020), increased public awareness of the need to reduce FWL. Consequently, research focusing on efficiently addressing FWL events in the FSC has intensified. In particular, the use of new digital technologies to tackle FWL has increasingly been adopted. Indeed, digitalization plays a crucial role in enhancing food security with improvements in efficiency, transparency, accuracy, and response time within the FSC (Joshi and Sharma, 2022). However, existing research often examines the isolated effects of single digital technologies within specific FSC phases. This includes for example: image processing at the producing phase (Mohammadi et al., 2015), handling phase (Arzate-

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https://doi.org/10.1016/j.techfore.2025.124175
Received 28 November 2023; Received in revised form 14 April 2025; Accepted 24 April 2025
Available online 5 May 2025

Vázquez et al., 2011) and processing phase (Mehdizadeh, 2022); artificial intelligence at the producing phase (Pandey and Mishra, 2024), storage phase (Zeymer et al., 2021), processing phase (Cen et al., 2024), retail phase (Miguéis et al., 2022) and consumption (Lubura et al., 2022); digital platform at the producing phase (Amiri-Zarandi et al., 2022), retail phase (Voldnes et al., 2021) and consumption phase (Heidenstrøm and Hebrok, 2022). Additionally, other research explores the use of a single technology throughout the whole FSC, e.g. Big Data (Cicculo et al., 2022), Blockchain (Kayikci et al., 2022b), Internet of Things (Ahmadzadeh et al., 2023) or Digital Twin (Singh et al., 2023). This body of work suggests significant literature on the adoption of digitalization to tackle FWL events. To date however, existing research literature remains fragmented (Margaritis et al., 2022), impeding a unified comparison of different digital technologies and making it difficult to draw comprehensive, substantive conclusions on their impact on various FWL events at different phases within the FSC framework. Given this gap, a recently published research survey emphasized the need to explore how to fully adopt digital technology and implement corresponding governance mechanisms in the whole FSC to promote effective collaboration, enhance information exchange, reduce FWL, and ultimately promote environmental, social, and economic goals (Trevisan et al., 2024).

Within this context, this study aims to make a significant contribution to the FWL and digitalization domains in response to the above-identified research avenues. The purpose of the study is fourfold. First, it involves adopting a systematic literature review (SLR) approach to identify advanced digital technologies currently employed to address complex FWL events within the FSC. Second, the study aims to expound on the main applications of these digital technologies within the FSC. It seeks to identify how digital deployments vary for different types of FWL events across various FSC phases. Third, the study aims to establish a comprehensive digital FWL network management framework, underpinned by the insights gained from the SLR. This framework is designed to enhance the understanding of tackling complex FWL events within the FSC through practical digitalization approaches. Fourth, this study aims to analyze the research trends, sustainable impact, and deployment barriers of digital technologies in reducing FWL, pointing out future research lines. To the best of our knowledge, no existing research systematically integrates the application methods of multiple digital technologies across different FWL events and FSC phases. Thus, the value of this research lies in providing a unified and comprehensive perspective, aiming to apply multiple digital technologies to mitigate current FWL challenges. Additional value in this research emerges from a detailed analysis of how these technologies are applied and deployed within the FSC framework for addressing various FWL events.

The rest of this paper is structured as follows: Section 2 presents the theoretical contextualization of the review. Section 3 formulates the research methodology and profiling. Section 4 presents the findings and results. Section 5 reviews these findings to develop a digital FWL network management framework. Finally, Section 6 analyzes and discusses the reviewed results and summarizes the academic and practical contributions, conclusions, limitations and future research directions.

2. Conceptual background and FWL contextualization

To delineate the context and scope of our research, we have adopted a definition of food as any substance consumed by an organism to provide nutrition and energy (C. E. (n.d.)) with a focus on food that is widely accepted by humans and active in the FSC. Over the past decades the FSC has been defined as the flow of food-related services and products along the value-added chain, aimed at minimizing costs and maximizing value for customers (Folkerts and Koehorst, 1997). The FSC is more complex than other supply chain due to factors like perishability, food-related infrastructure, and stakeholder interaction (Mithun Ali et al., 2019). Low efficiency and lack of transparency due to the FSC's complexity contribute to the occurrence of FWL (Aramyan et al., 2021).

Food waste and food loss are intertwined and span the entire FSC (Kotykova et al., 2021), but they are distinctly defined terms. Food loss generally refers to the reduction in edible food quality or quantity at any stage of the FSC, meaning food that spoils or spills before reaching retail or final product stages (FAO, 2020). Conversely, food waste is defined as food that is of good quality and suitable for human consumption but is discarded instead of being consumed (Vilariño et al., 2017). It is noteworthy that according to the commonly used definition, food loss and food waste do not include waste that occurs during primary production, which includes the initial stages of crop and animal production but begins with the harvesting process (Patinha et al., 2017). However, the scope of this work is broader as it also includes the pre-harvesting processes of primary production. Previous literature emphasizes the potential of innovative technologies within the FSC to address the issues of FWL (Parfitt et al., 2010). Consequently, research on the adoption of digitalization to enhance FSC efficiency has gained prominence (Abideen et al., 2021).

Digitalization has varying definitions across fields, in this research

Table 1
Main Food waste and loss (FWL) have always been (FWL) events within food supply chain.

	Production	Storage & Handling	Packaging & Processing	Retail & Distribution	Consumption
Micro	• Poor crop health (disease, drought, weed, etc.) • Poor agricultural animal health (disease, feeding, sanitation, etc.) • Birds and pests that eat crops • Low agricultural task efficiency • Misjudge crop ripeness or classification	• Improper storage environment (temperature, humidity, pests, etc.) • Inefficient handling process (washing, ripening, etc.) • Inefficient food quality monitoring	• Inefficient processing flow or techniques • Poor food packaging techniques • Process residues, by products, and losses • Inefficient food quality monitoring	• Misjudge food shelf-life or expiration date • Improper inventory management	• Misjudge or neglect food expiration • Errors in cooking resulting in waste • Improper preservation conditions • Lack of the awareness and methods to tackle FWL
Meso	• Inefficient agricultural information acquisition and monitoring • Failure to meet quality or aesthetic standards • Inconsistent with market demand		• Failure to meet quality or aesthetic standards • Inconsistent with market demand	• Failure to meet quality or aesthetic standards • Lack of connection among supplier, retailer, and consumer • Inconsistent with market demand • Inefficient sale strategy	• Failure to meet quality or aesthetic standards • Lack of connection among consumers • Misjudge food demand quantity
Macro	• Inefficient food-related data information monitoring, transmission, sharing, and management • Inefficient food-related data processing, analysis, and prediction • Inefficient FSC coordination and management • Low transparency and traceability of FSC				

This table is self-elaborate.

Table 2
Summary of related keywords for literature search.

Food waste and loss	Food supply chain	Digitalization
Food waste*; Food loss*; Food wastage*; Waste of food*; Food leftovers*	Logistics*; Supply chain*; Agricultural*; Harvest*; Post-harvest*; Farm*; Handling*; Storage*; Retail*; Transp-ortation*; Manufacturing*; Packaging*; Distribution*; Supplier*; Consumption*	Digitalization*; Digitalisation*; Digital transformation*; Digital technology*; Digital*; Industry 4.0*; Smart*; Cloud computing*; Digital platform*; Social media*; Internet of Things*; Digital twin*; Blockchain*; Artificial intelligence*; Big data*; Drone*; Robot*; Satellite*; Unmanned Aerial Vehicles*; Information technology*; Additive manufa-cturing*; Image processing*; Radio frequency identification*

we adopted a conceptualization of digitalization from a business-oriented perspective: the adoption of digital technologies to transform business models and create value (Bloomberg, 2018). Generally, digital technology encompasses electronic devices, tools, resources and systems for data generation, processing or storage, integrating communication, information, and computing technologies (Bharadwaj et al., 2013; Hennessy et al., 2005). Overall, digitalization in supply chain management aims to improve dynamics, flexibility, accuracy, stability, and autonomy (Ivanov et al., 2019), and enhances cross-functional and cross-enterprise integration (Fatorachian and Kazemi, 2021). Therefore, digitalization is laying the foundation for the development of digitization, smartness, and automation in organizations (Erol et al., 2016).

The digitalization of the FSC has played a significant role in tackling FWL events (Annosi et al., 2021). Indeed, a range of FWL events within FSC have been discussed by experts from a digitalization solution perspective including: crop health management (Seymour et al., 2021), crop ripeness recognition and classification (Gao et al., 2020), agricultural animal health management (Senturk et al., 2023; Paul et al., 2022), storage management (Zhang et al., 2024; Zhao et al., 2024a), food processing management (Jagtap et al., 2021), food recycling and reprocessing (Hassoun et al., 2023b), shelf-life management (Sciortino et al., 2016), inventory management (Miguéis et al., 2022), data generation, collection and monitoring (Saban et al., 2023; Annosi et al., 2021), food relevant information management (Amaral and Orsato, 2023), resilience in supply chain network (Hassoun et al., 2024a; Singh et al., 2023), collaboration and coordination among stakeholders (Amentae and Gebresenbet, 2021), and enhancement of public awareness (Young et al., 2017).

The FSC is usually divided into five stages (FAO, 2013):1. Production; 2. Handling & Storage; 3. Processing & Packaging; 4. Distribution & Retail; 5. consumption. The production stage is the beginning of the FSC and includes activities such as food growth, cultivation, development and harvest. Handling & storage comprises simple routine operations (e.g., rinsing, fruit ripening) carried out after the food is harvested, together with the storage of food to ensure the quality (Parwez, 2014). Processing & packaging refer to the activities for making food reach different kinds of requirements including edible standard, beautiful appearance, prolonged shelf life (Ju et al., 2017). Distribution & retail is the stage where processed food is transported to retailers, and retailers sell food to consumers (Ju et al., 2017). Finally, consumption conceptualizes the phase when the food is consumed, which marks the end of the FSC . Food loss typically takes place in the first three phases, whereas food waste predominantly occurs in the latter two phases (Trevisan et al., 2024). To tackle the occurrence of FWL it is essential to analyze the structural and circumstantial nature of FWL causes. Categorizing these causes allows for a systematic mapping of different FWL events within the FSC, aiding a comprehensive approach to tackling FWL.

Table 3
Inclusion and exclusion criteria for the research.

Inclusion Criteria	Exclusion Criteria
Articles focus on digital technology to directly or indirectly tackle specific FWL events	The abstract of the article is unavailable
Articles focus on the application of digital technology in the whole FSC	The language of article is not English
Peer-review journal publications	Book chapters, conference papers, reports, or other grey literature
Articles published from January 2014 to September 2024	Research on tackling FWL pays little or no attention to digitalization
	Research related to other academic sectors, such as novel materials, additives, chemistry, dietary patterns or nutrition, etc.

Previous literature has categorized FWL events into three levels: micro, *meso*, and macro (Diaz-Ruiz et al., 2018; Balaji and Arshinder, 2016; Parfitt et al., 2010): 1.Micro-level events are those whose causes are direct as described by different stakeholders throughout the FSC (Blakeney, 2019); 2.Meso-level events are structural events driving the occurrence of FWL at micro-level (Canali et al., 2016); 3.Macro-level events are defined as systematic events causing lower level events (Diaz-Ruiz et al., 2018). This study compiles these events in Table 1 and proposes digital solutions to prevent them in the future.

Likewise, the sustainable development goals proposed by the United Nations for the food industry (United Nations, 2018) highlight the potential of digitalization to develop a sustainable FSC able to tackle the occurrence of FWL (Mahroof et al., 2022). To date however, most studies focus on the application and limitations of individual technologies, while few explore multiple technologies (Yadav et al., 2022a). The scarcity of this research direction motivates our study, which adopts a comprehensive and multi-technology perspective throughout the FSC. We envision digital technologies playing a distinctive role in FWL events, from individual FSC phases to overall management. Our goal is to illustrate a comprehensive integration of digital technologies, detailing their applications and deployments for various FWL events in different FSC phases. This analysis aims to guide relevant stakeholders in adopting appropriate digital technologies for specific FWL events, understanding deployment strategies, and utilizing them effectively. In summary, this study seeks to summarize relevant literature from 2014 to 2024, elaborate on integrating multiple digital technologies to address FWL events, and explore future research directions.

3. Research methodology

This research adopts a systematic literature review (SLR) approach - a detailed, rigorous, established, and proven methodology for supporting decision-making (Tranfield et al., 2003). This approach involves collecting a vast array of literature around a topic, analyzing various perspectives and research methods, and gathering sufficient knowledge and evidence to establish a solid theoretical basis. This process also ensures that conclusions and results are consistent and reliable (Akobeng, 2005). Furthermore, SLR enhances the credibility of research, thereby enhancing the rationality and clarity of the various results present in the literature (Gough et al., 2017). Over the years, SLR has been extensively utilized in management and business research, particularly in fields related to FSC management (Bayir et al., 2022; Yadav et al., 2022a; Chauhan et al., 2021) and has been increasingly linked with studies on digitalization (Masi et al., 2021; Núñez-Merino et al., 2020; Sharma et al., 2020). Given this context, SLR is a suitable methodological choice to achieve the aim of our study.

Following the guidelines set out by Tranfield et al. (2003) and Denyer and Tranfield (2009), our SLR is conducted in three phases: 1. planning phase – identifying the review's needs, selecting literature databases, identifying keywords and search terms, and establishing

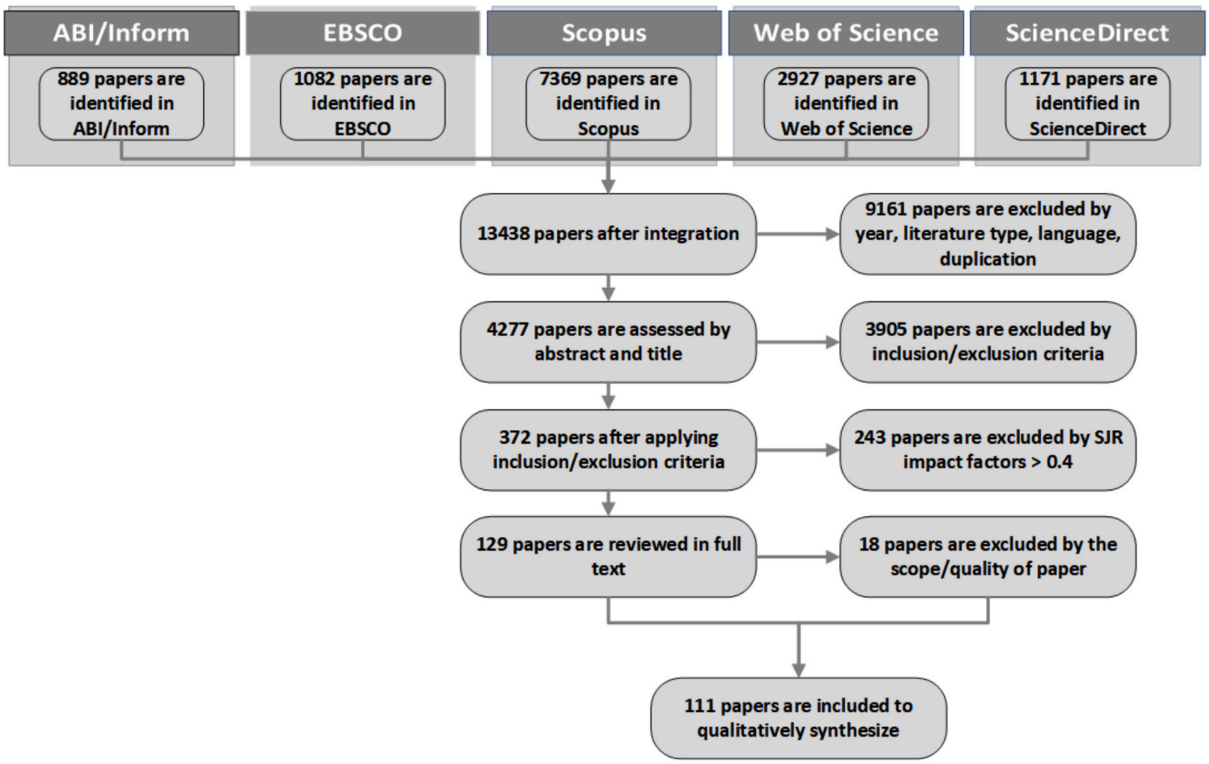

Fig. 1. The process steps of systematic literature review.

exclusion and inclusion criteria; 2. development phase – the process of extracting, analyzing, and synthesizing literature data; 3. reporting phase – reviewing findings and disseminating knowledge.

3.1. Planning phase

In the initial stage of our research, we conducted a pilot trial to firstly understand the scope of literature relevant to our research topic. Focusing on the integration of multiple digital technologies to address FWL events within the FSC, we pre-screened keywords from previous SLR literature on similar topics (Rolker et al., 2022; Chauhan et al., 2021; Van der Werf and Gilliland, 2017). This process helped us identify and develop a series of keywords related to FWL and FSC. Additionally, considering the extensive coverage of digitalization at the application level in management and business fields, we identified initial keywords related to digitalization from pertinent literature (Matt et al., 2023; Zheng et al., 2021; Ghobakhloo et al., 2021). The selection of keywords aimed to be broad enough to capture the scope of the research while being specific enough to locate literature relevant to our topic (Sangwa and Sangwan, 2018; Thomé et al., 2016). Thus, we replicated the keyword selection method used in similar thematic SLR studies (Chauhan et al., 2021). An initial keyword set was used to search for literature in Google Scholar. After reviewing the first 100 search results, the keyword set was refined and finalized as detailed in Table 2.

Subsequently, we determined the scholarly databases for collecting academic literature. While most previous SLR studies have focused on two to three databases, such as Science Direct, Scopus, and Web of Science (Chauhan et al., 2021; Dhir et al., 2020), we aimed to cover studies as comprehensively as possible and minimize research omissions and biases (Durach et al., 2017), we therefore adhered to a rigorous, systematic, and synthesized review procedure (Paul et al., 2021).

This research encompasses literature from five scholarly databases: Scopus, Web of Science, ABI/Inform, Science Direct, and EBSCOhost. Our decision aligns with the approach of Stangherlin et al. (2018) who also covered five scholarly databases. Moreover, these selected databases are frequently referenced in FWL research (Moraes et al., 2021). Given the rapid expansion and diversification of research on sustainable FSC in recent years (Kumar et al., 2022), sampling from these databases is expected to strengthen our research perspective by broadening the scope of literature sources.

Our search strings were constructed using the final set of keywords combined with Boolean connectors (OR and AND). Due to the varying search engines across different databases, the corresponding search strings were slightly modified as needed. Our strategy for constructing search strings can be summarized as follows: synonyms are connected within an individual item using OR. For example, the phrase ("food waste" OR "food loss" OR "food wastage" OR "waste of food") constitutes a synonymous item for FWL. Different items are then connected using AND, allowing the search string to be expressed generically as: ("FWL synonyms") AND ("digitalization synonyms") AND ("FSC synonyms"). In databases with limitations on search string length, we iterated through "digitalization synonyms" and "FSC synonyms" while keeping the "FWL synonyms" fixed, to ensure comprehensive coverage of the literature.

In order to enhance the precision of our search and manage the review workload efficiently we concentrated our search efforts on the 'title, abstract, and keywords' sections of articles. Despite this focus, the volume of literature remained substantial, underscoring the importance of meticulous literature screening. Consequently, we established a set of inclusion and exclusion criteria, detailed in Table 3. These criteria were developed by observing similar thematic SLR works, such as those by Chauhan et al. (2021), Kaur et al. (2021), and Dhir et al. (2020). It is important to note that this research included only journal articles, while book chapters, reports, conference papers or grey literature were excluded due to potential quality uncertainties arising from the lack of a peer-review process (Adams et al., 2017).

Our research was conducted in September 2024, focusing on a span of publications from January 2014 to September 2024. This timeframe was selected based on several considerations. Firstly, a significant portion (over 80 %) of the literature on sustainable FSC-related topics, including FWL, has been published since 2014 (Kumar et al., 2022).

Table 4
Description of digital technologies present in this review.

Digital technology	Description
Additive Manufacturing (AM)	The material joining technologies that can manufacture 3D objects in layers without cutting tools or molds. (Gebhardt, 2011)
Artificial Intelligence (AI)	A system realizes specific tasks and goals by interpreting and analyzing input data, learning from these data, and flexibly adapting and using these learning results to generate output. (Kaplan and Haenlein, 2019)
Big Data (BD)	A large number of complex unstructured and structured datasets that are quickly generated from various sources, and analyzed to produce actionable insights and establish competitive advantages for continuous value delivery. (Chandarana and Vijayalakshmi, 2014)
Blockchain	A fully distributed, immutable, shared business system which can effectively record transactions and track assets. (Agrawal et al., 2021)
Cloud Computing (CC)	A model for supporting on-demand, convenient, ubiquitous, location-independent and device-independent network access to configurable and shared computing resources (such as applications, storage, servers and networks services), which can be quickly released and provisioned with minimal service provider interaction or management work. (Marston et al., 2011; Mell and Grance, 2011)
Digital Platform (DP)	A multisided network that promotes interactions among different but interdependent user groups (such as producers, retailers, consumers, etc.). (Asadullah et al., 2018)
Digital Twin (DT)	A virtual replica of a physical object (process, system, product), which updates data in real time throughout its life cycle and helps decision-making by simulating reality. (Tao et al., 2018)
Image Processing (IP)	A signal processing method, which takes image data as input and operates through some algorithms, so as to output images or valuable information associated with the images. (Gonzalez, 2009)
Internet-of-Things (IoT)	A distributed network that connects physical devices and objects, which can act or sense on the environment, and can communicate with each other and other machines. (Davies, 2015)
Information and Communication Technology (ICT)	A series of technical resources and tools used to create, store, transmit and share information (such as computers, internet and telephones, etc). (Alkamel and Chouthaiwale, 2018)
Radio Frequency Identification (RFID)	The technology of using radio waves to automatically locate and identify people or objects. (Roberts, 2006)
Robot	A machine that can remotely control or automatically complete a series of high-efficiency and high-precision complex actions through computer programmes, and it can perform specific tasks with little or no human intervention. (Ben-Ari et al., 2018)
Satellite communication & monitoring	Any technology supported by celestial bodies orbiting the earth, including the data information (e.g., communications and images) collected and generated by celestial bodies. (Maini and Agrawal, 2011)
Social Media (SM)	Interactive technologies that can promote the sharing, communication, cooperation and creation of individual information and ideas based on the Internet. (Obar and Wildman, 2015)
Sensor	Sensors usually refer to devices, machines or modules that are used to detect changes or events in the environment, by converting them into electrical signals and sending information to other electronic devices. (Wilson, 2004)
Unmanned Aerial Vehicles (UAV)	Unmanned aircraft operated either intermittently or completely autonomously by self-contained programmes, radio remotes, or on-board computers, can perform specific missions inside and outside the Earth's atmosphere by carrying various types of payloads. (Bao et al., 2024)

Furthermore, this period marks an increasing reliance on digitalization within the sustainable FSC (Annosi et al., 2021), accompanied by a notable rise in academic literature and discussion on the topic (Kayikci et al., 2022b; Yadav et al., 2022a; Joubert and Jokonya, 2021). By extending the review period to 10 years, we aimed to ensure the comprehensiveness and relevance of our research.

3.2. Development phase

During the development phase, we employed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework to guide our review process (Moher et al., 2010). The PRISMA framework offers clear guidance for conducting and reporting SLR (Stovold et al., 2014). It also allows readers and reviewers to be systematically informed about the research process and findings, thereby enhancing the quality of methodology and reporting (Page et al., 2021). The PRISMA flow diagram of our review work is presented in Fig. 1. The detailed review process is outlined as follows:

1. Utilizing the search string developed during the planning stage, we conducted a literature search of five scholarly databases: Scopus, Web of Science, ABI/Inform, Science Direct, and EBSCOhost.
2. The search results from these databases provided a total number of 13,438 papers. After merging these results in Zotero for automatic full-text download and duplication removal and applying filters for publication year, literature type, and language, we narrowed this down to 4277 papers, as shown in Fig. 1.
3. We then screened titles and abstracts of these papers based on our exclusion and inclusion criteria (Table 3), reducing the number from 4277 to 372.
4. Given the high number of remaining papers, we referred to similar thematic SLR literature and decided to use the SJR (SCImago Journal Rank) impact factor as an additional exclusion criterion (Solarte-Montufar et al., 2021; Thomé et al., 2021). We set the threshold at 1.5, as per the seminal work of Thomé et al. (2021). This step further reduced the papers to those published in journals with an SJR impact factor above the threshold.
5. This selection process reduced the number of papers from 372 to 129. Upon full-text review, we found that some papers, although meeting the inclusion criteria in their abstracts, were not suitable in terms of quality and scope. Ultimately 111 papers were selected for the review. We used Microsoft Excel to systematically extract and structure content from these papers, including descriptive information and details pertinent to our research questions. The extraction table is detailed in Appendix A (Table 12).
6. Completing the review and extraction, we held a meeting to discuss and analyze the results. This led to the identification of six FSC deployment phases: production, handling & storage, processing & packaging, retail & distribution, consumption, and the whole FSC.
7. We conducted an in-depth analysis of each paper, extracting information on digital technology applications, corresponding FWL events, FSC deployment phases, sustainability impact, and deployment barriers. We employed a coding method by Saldaña (2021) and Xiao and Watson (2019) to systematically synthesize these results, organizing them under various themes representing the FSC phases in which digital technologies were deployed. An illustrative example is shown in Appendix B (Fig. 9).
8. Finally, we reviewed each other's work to address any shortcomings, add details, and refine the overall review.

During the development phase, we implemented screening criteria, including SJR impact factor, publication year, language, and type of literature, to narrow down the large initial dataset and ensure that the selected papers met a defined scope and quality standard. However, relying on these exclusion criteria may inadvertently omit relevant or innovative research from emerging fields or new publication outlets that

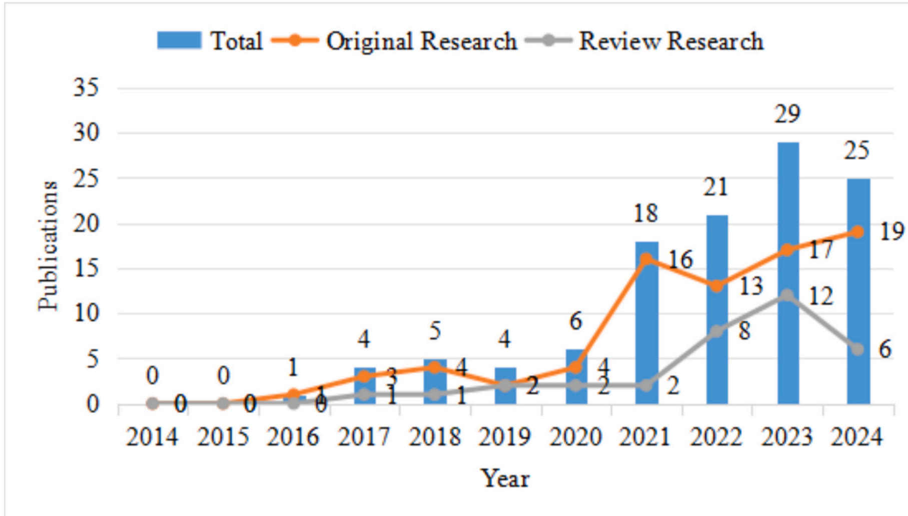

Fig. 2. Year-wise publications.

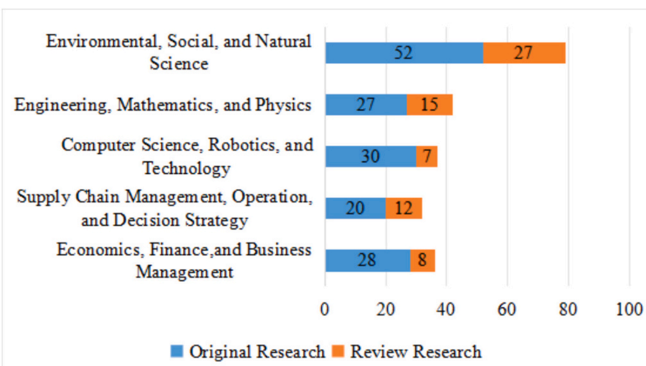

Fig. 3. Number of publications related to different disciplines (*Some articles are multidisciplinary and included in more than one subject area**).

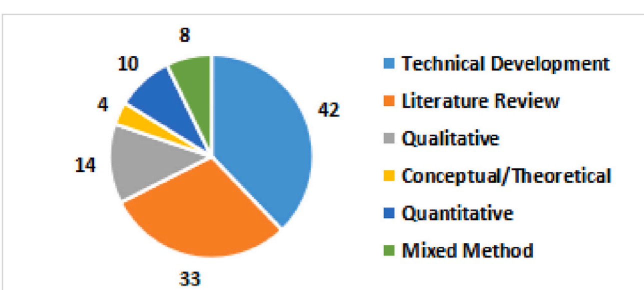

Fig. 4. Number of publications using different research methodologies.

have not yet accumulated sufficient citations to achieve a high impact factor. As a result, our coverage may be limited, particularly in capturing nascent or interdisciplinary contributions. While these criteria help promote consistency across selected publications and research themes, they may also constrain the representativeness of the current literature landscape, leading to the inevitable omission of potentially influential but lesser-known studies, a limitation we acknowledge later in the paper.

3.3. Reporting phase

In the following sections we have detailed the results of our systematic literature review. The focus primarily was on the following six perspectives: 1. the review and description of digital technologies; 2. the statistical information on the included papers; 3. the specific application strategies for digital technologies to FWL events across the FSC; 4. the collaboration among digital technologies in reducing FWL; 5. the impact of digitalization on the sustainability of FSC; 6. the barriers of digitalization on FWL. This analytical strategy was inspired by SLR analyses on similar topics as found in the research of Rad et al. (2022), Yadav et al. (2022a), Yadav et al. (2022b), and Sharma et al. (2020).

The statistical information on the included papers mainly identified the number of annual publications, types of studies, subject areas, and digital technology domains. Notably, since the review research has included some original research, we separated all statistics into review research and original research to avoid the distortion of statistical results. In addition, to present the statistical information in a clear and organized manner in the study type subsection this study drew upon similar thematic work by Kazancoglu et al. (2021b) and Jabbour et al. (2020). Five main categories were established: 1. environmental, social, and natural science; 2. economics, finance, and business management; 3. supply chain management, operation, and decision strategy; 4. computer science, robotics, and technology; 5. engineering, physics, and mathematics. Regarding the subject area subsection, the categorization is based on the seminal works of Rad et al. (2022) and Yadav et al. (2022b). following their approach, we classified the included articles into six groups: 1. technical development/improvement; 2. literature review; 3. qualitative study; 4. quantitative study; 5. mixed method; 6. conceptual/theoretical study.

4. Findings and results

4.1. Review and description of digital technologies

As previously noted, the intersection of research between FWL and digital technologies is fragmented and dispersed (Margaritis et al., 2022). This fragmentation leads to diverse research perspectives and a range of descriptions for different digital technologies applicable in various domains (Rowan, 2023; Ramanathan et al., 2023; Yadav et al., 2022a). Therefore, before reporting the results and findings of this study, and in order to ensure clarity and avoid any potential misunderstandings, it is crucial to establish working definitions for commonly used digital technology terms. To this end, Table 4 presents detailed descriptions of the 16 digital technologies identified in our analysis. These technologies are described based on two criteria: 1. their applicability in the context of the FSC, and 2. their capacity to

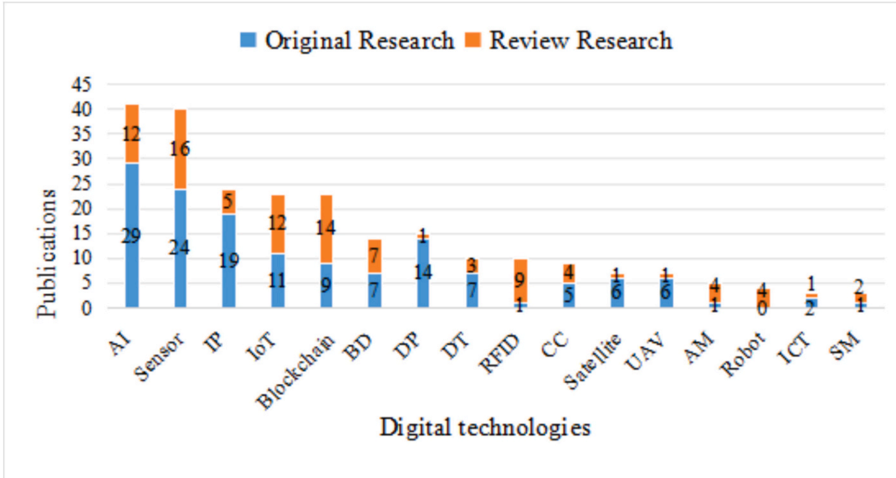

Fig. 5. Number of publications involving different digital technologies (*A few articles involve multiple technologies**).

comprehensively encapsulate the scope and inherent capabilities of the digital technology.

A series of digital technologies listed in Table 4 show significant interdependence, and they work together to enhance capabilities in various fields. For example, AI relies heavily on BD to effectively train AI models so that the accuracy and performance of AI algorithms are closely related to the availability of a large number of high-quality data sets (Peng et al., 2024). Similarly, IoT frameworks are usually equipped with sensors to collect data, combined with RFID to complete device identification, and maintain communication connection with the central system through wireless networks to form a complete IoT ecosystem (Song et al., 2024). In addition, blockchain usually supports the storage and processing of data collected by sensors under IoT infrastructure (Wu et al., 2022). These interrelations highlight the collaborative nature of contemporary digital technology, and promote innovation and efficiency through integrated applications.

4.2. *Statistical information on the included papers*

4.2.1. *Publications by year*

Fig. 2 illustrates the annual distribution of the 111 publications analyzed in our study, revealing a continuous upward trend since 2019. This pattern not only corroborates the earlier assertion that over 80 % of the literature on sustainable FSC-related topics was published from 2015 to 2023 (Kumar et al., 2022), but also aligns with our identification of an increasing trend in academic literature and discussions in this field (Kayikci et al., 2022b; Yadav et al., 2022a; Joubert and Jokonya, 2021).

4.2.2. *Publications by subject areas*

Fig. 3 shows that research on implementing digitalization to address FWL events within the FSC spans five main subject areas. Regarding the distribution of original research articles within this SLR, the most prominent subject area is environmental, social, and natural science, which encompasses 52 out of 78 articles (67 %). This is closely followed by computer science, robotics, and technology, accounting for 30 out of 78 articles (38 %). Additionally, out of the 78 original research articles, 27 (35 %) and 28 (36 %) are classified under engineering, physics, and mathematics, and economics, finance, and business management, respectively. The least represented subject area is supply chain management, operation, and decision strategy, comprising 20 out of 78 articles (26 %). Similarly, the review research focuses on environmental, social, and natural science, with 27 out of 33 articles (82 %). The study area with the largest difference is computer science, robotics, and technology, representing only 7 out of 33 articles (21 %).

4.2.3. *Publications by study type*

Fig. 4 categorizes the research methodologies applied in the articles included in this review. Our analysis reveals that the majority of articles focus on technical development /improvement, with 42 out of 111 (37 %) falling into this category, with conceptual/theoretical studies jointly accounting for 41 % of the total. Literature review methodologies are used in 33 out of 111 articles (30 %). Similarity, quantitative, qualitative, and mixed-method studies collectively represent 32 out of 111 articles (29 %).

4.2.4. *Publications by technology domain*

A notable finding in our research is the integrative study on the application of various digital technologies to address FWL issues. Fig. 5 details the frequency of use of 16 technological domains across the 111 selected articles. Notably, AI leads in usage, being featured in 29 original research articles, which constitutes 37 % of the total. Sensor and IP are also prominent, accounting for 30 % and 24 % of the original papers respectively. In contrast, there are 11 technological domains with less original research. These include the blockchain with 9 mentions, BD with 7, DT with 7, satellite communication & monitoring and UAV each with 6, CC with 5, ICT with 2, SM, RFID, and AM each with only 1, and robot with no mention. Similarly, the review research follows the distribution rules found in the original research. Among them, the technologies that show significant differences in numerical statistics include blockchain, RFID, AM, and robot. Compared with the original research, these technologies have been discussed more in the review research.

4.3. *The deployment of digital technologies in tackling FWL events within FSC: Deployment phases, application methods, and corresponding FWL events*

In this subsection, we offer a holistic and comprehensible overview of how digital technologies are applied to address FWL events within the FSC. Drawing from the analysis of 111 articles from our review and referencing typical FWL events within the FSC (Table 1), we have developed three primary categories: application methods, FWL events, and FSC deployment phases, as mentioned in the development stage of our methodology. These categories include Production (Table 5), Handling & Storage (Table 6), Processing & Packaging (Table 7), Retail & Distribution (Table 8), Consumption (Table 9), and the Whole FSC (Table 10). We present the applications of 16 digital technologies identified in our research, organized cohesively across these categories. This presentation method clearly delineates each digital technology's deployment in various FSC phases, along with their specific application methods for different FWL events.

Table 5
Production phase.

Technology	Application method	FWL event	Publication
Artificial Intelligence	To detect, classify, and predict the health condition of crops (e.g., disease, pests, weeds, etc.)	Poor health management of crops (micro), Birds and pests that eat crops (micro)	(Bao et al., 2024), (Pandey and Mishra, 2024), (Aggarwal et al., 2024), (Demilie, 2024), (Liu et al., 2024), (Saranya et al., 2023), (Braguy et al., 2021), (Abade et al., 2021), (Chen et al., 2021), (Karlekar and Seal, 2020), (Jimenez et al., 2020)
	To evaluate and classify the ripeness of crops, and judge the appropriate crop management accordingly	Misjudge the ripeness or classification of the crops (micro)	(Razavi et al., 2024), (Gao et al., 2020), (Hassanzadeh et al., 2021), (Garcia-Manso et al., 2021)
	To assist other automated technologies to perform efficient and precise agricultural tasks	Low agricultural task efficiency (micro)	(Pandey and Mishra, 2024), (Rajendran et al., 2024)
	To detect, classify, and predict the health condition of agricultural animal	Poor health management of agricultural animals (micro)	(Pandey and Mishra, 2024)
	To predict and assess the agricultural yield or demand, so as to assist make decisions	Inconsistent with market demand (*meso*)	(Pandey and Mishra, 2024), (Saranya et al., 2023), (Farooq et al., 2022), (Vergopolan et al., 2021), (Li et al., 2018)
	To predict and assess the disaster risk of threats to agriculture (e.g., drought, flooding, pests, etc.)	Poor health management of crops (micro)	(Pandey and Mishra, 2024), (Li et al., 2021), (Vergopolan et al., 2021)
Digital Platform	To share agricultural knowledge, information, and experience, so as to develop and implement counteracting measures.	Inefficient agricultural information acquisition and monitoring (*meso*)	(Dong et al., 2024), (Rossi et al., 2023)
Image Processing	To evaluate, identify, and classify the health condition of crops (e.g., disease, pest, weeds, etc.)	Poor health management of crops (micro), Birds and pests that eat crops (micro)	(Bao et al., 2024), (Aggarwal et al., 2024), (Demilie, 2024), (Liu et al., 2024), (Hu et al., 2023), (Braguy et al., 2021), (Karlekar and Seal, 2020)
	To evaluate and classify the ripeness or classification of crops, and judge the appropriate crop management accordingly	Misjudge the ripeness or classification of the crops (micro)	(Razavi et al., 2024), (Hassanzadeh et al., 2021), (Garcia-Manso et al., 2021)
	To assist other automated technologies to perform efficient and precise agricultural tasks	Low agricultural task efficiency (micro)	(Rajendran et al., 2024)
	To identify the health conditions of livestock, poultry, and fishery (e.g., disease, feeding, breeding, etc.)	Poor health management of agricultural animals (micro)	(Saberioon et al., 2017)
Robot	To efficiently and precisely perform agricultural tasks	Low agricultural task efficiency (micro)	(Rajendran et al., 2024)
Sensor	To monitor the health and environmental conditions of livestock, poultry and fishery (e.g., temperature, humidity, disease, feeding, etc.)	Poor health management of agricultural animals (micro)	(Senturk et al., 2023), (Paul et al., 2022), (Saberioon et al., 2017)
	To monitor the health and environmental conditions of crop growth (e.g., temperature, humidity, disease, soil, weeds, pests, etc)	Poor health management of crops (micro), Birds and pests that eat crops (micro)	(Aggarwal et al., 2024), (Hasan et al., 2024), (Geckeler et al., 2023), (Senturk et al., 2023), (Hu et al., 2023), (Saranya et al., 2023), (Paul et al., 2022), (Jimenez et al., 2020)
	To assist other automated technologies to perform efficient and precise agricultural tasks	Low agricultural task efficiency (micro)	(Rajendran et al., 2024)
Satellite communication & monitoring	To generate and collect satellite data related to agriculture (e.g., land surface temperature, optical-based vegetation indices, solar-induced fluorescence, soil moisture, etc.), so as to predict the agricultural crop yield	Inconsistent with market demand (*meso*)	(Dhakar et al., 2022), (Vergopolan et al., 2021), (Karthikeyan et al., 2020)
	To generate and collect satellite data related to agriculture (e.g., land surface temperature, precipitation, soil moisture, etc.), so as to predict, assess, and quantify disaster risks (e.g., drought, flooding, diseases, etc.)	Poor health management of crops (micro)	(Zhao et al., 2024b), (Li et al., 2021), (Vergopolan et al., 2021), (Karthikeyan et al., 2020), (Song et al., 2018)
Unmanned Aerial Vehicles	To efficiently perform digital monitoring and management in agriculture tasks.	Inefficient agricultural information monitoring (*meso*)	(Bao et al., 2024), (Geckeler et al., 2023), (Hu et al., 2023), (Saranya et al., 2023), (Paul et al., 2022), (Hassanzadeh et al., 2021)

4.4. Collaboration among digital technologies on reducing FWL

This section examines the collaboration among digital technologies in technical development literature. As demonstrated in Fig. 6, most research focuses on the integration of AI and IP technology, which is used to identify, classify, and predict the quality of crops or food. Next, the links between IoT and sensors also appear frequently, which are used to collect data in the food supply chain and realize real-time detection. In addition, the combination of AI and sensors is often discussed for data collection and analysis to assist decision-making. Other digital technologies, such as blockchain, CC, satellite communication & monitoring, BD, and UAV, mainly focus on the collaborative application of the above four technologies.

Some articles mention the collaboration among digital technologies on FSC. De Souza et al. (2021) state that combining different digital technologies, such as BD and AI, to support the decision-making of FWL in an uncertain environment may be a challenge which has not yet been fully addressed. Yadav et al. (2022b) analyzed the Industry 4.0 technology in the FSC and propose that most of these technologies are used as independent solutions at present lacking integration. Pakseresht et al. (2023), Giganti et al. (2024), and Yang et al. (2023) pointed out that blockchain technology stands alone as an end-to-end solution but needs to be combined with other technologies (such as sensor networks, IoT, AI, and CC) to have a long-term impact on the sustainability of the FSC. Hassoun et al. (2024b) highlighted that when smart sensors are combined with AI and robotics, they have the potential to realize better automatic dairy processing operations and product quality control, and to further improve waste management. Similarly, Hassoun et al. (2024a) emphasize how to use IoT, blockchain, AI, BD, and RFID technologies alone or in combination to tackle FWL caused by insufficient monitoring and tracking of food quality.

4.5. The impact of digitalization on the sustainability of FSC

As the statistics in Fig. 3 show, the digitalization-topic articles included in this SLR align with the initial assertion of this study: that

Table 6
Handling & storage phase.

	Application method	FWL event	Publication
Artificial Intelligence	To evaluate, classify, and predict the quality of food being stored or handled, based on environmental and food quality information.	Inefficient food quality monitoring (micro), Improper storage environment (micro)	(Wu and Tai, 2024), (Wang et al., 2024), (Pandey and Mishra, 2024), (Razavi et al., 2024), (Zhang et al., 2024), (Jiang et al., 2023), (Qu et al., 2023), (Stasenko et al., 2023), (Song et al., 2024), (Van De Looverbosch et al., 2022), (Ma et al., 2021), (Goel et al., 2020)
	To evaluate and predict the environmental information at storage sites, so as to reduce food loss caused by food deterioration.	Improper storage environment (micro)	(Zhao et al., 2024a), (Loisel et al., 2021)
Image Processing	To evaluate, classify the quality of food being stored or handled, based on the internal and external image of food	Inefficient food quality monitoring (micro), Improper food handling process (micro)	(Wu and Tai, 2024), (Wang et al., 2024), (Razavi et al., 2024), (Stasenko et al., 2023), (Van De Looverbosch et al., 2022), (Goel et al., 2020), (Wang et al., 2018)
	To detect the environmental information at storage sites (e.g., pests)	Improper storage environment (micro)	(Zhao et al., 2024a)
Sensor	To monitor the environmental information at storage sites (e.g., temperature, humidity, gas, sound, etc.), so as to reduce food loss caused by food deterioration or pests.	Improper storage environment (micro)	(Zhang et al., 2024), (Senturk et al., 2023), (Niu et al., 2024), (Yang et al., 2023), (Qu et al., 2023), (Song et al., 2024), (Loisel et al., 2021), (Wang et al., 2018), (Bogataj et al., 2017), (Sciortino et al., 2016)
	To monitor the quality of food being stored (e.g., color, pH, respiration, etc.), so as to reduce food loss caused by food deterioration or pests.	Inefficient food quality monitoring (micro)	(Wang et al., 2024), (Zhang et al., 2024), (Senturk et al., 2023), (Song et al., 2024), (Osinenko et al., 2021), (Ma et al., 2021), (Wang et al., 2018)

Table 7
Processing & packaging phase.

Technology	Application method	FWL event	Publication
Artificial Intelligence	To evaluate, classify, and predict the quality of food being processed, so as to optimize and control processing flow.	Inefficient processing flow or techniques (micro), Failure to meet quality or aesthetic standards (*meso*)	(Cen et al., 2024), (Hassoun et al., 2024b), (Hassoun et al., 2022)
	To judge and optimize the operation of food processing (e.g., cutting, sorting, packing, etc).	Inefficient processing flow or techniques (micro)	(Hassoun et al., 2024b), (Hassoun et al., 2023a)
	To predict the food market demand and adjust the food processing output accordingly.	Inconsistent with market demand (*meso*)	(Hassoun et al., 2024b), (Hassoun et al., 2023a)
Additive Manufacturing	To recycle residues, by-products, or low-quality food produced during processing, so as to produce qualified food.	Food processing residues and losses (micro), Failure to meet quality or aesthetic standards (meso)	(Seo and Shigi, 2024), (Hassoun et al., 2023a), (Yu and Wong, 2023)
	To efficiently and easily produce nutritious and visually appealing food products with minimal or zero waste.	Food processing residues and losses (micro), Failure to meet quality or aesthetic standards (meso)	(Hassoun et al., 2024b), (Hassoun et al., 2023a)
	To enhance food packaging technology by creating and embedding devices (e.g., sensor, RFID tag) in food packaging to monitor food quality.	Poor packaging techniques (micro)	(Tracey et al., 2022)
Image Processing	To evaluate and classify the quality of food being processed, so as to optimize and control processing flow.	Inefficient processing flow or techniques (micro), Failure to meet quality or aesthetic standards (meso)	(Cen et al., 2024), (Jagtap et al., 2021)
Robot	To efficiently and precisely perform the operations of food processing and packaging, so as to reduce food production time and loss.	Inefficient processing and packaging flow or techniques (micro)	(Hassoun et al., 2023a), (Hassoun et al., 2024b), (Hassoun et al., 2022)
Radio Frequency Identification	To transmit food quality information and track logistics by installing RFID tags on food packaging, so as to help judge food quality in subsequent FSC.	Poor packaging techniques (micro), Inefficient food quality monitoring (micro)	(Upadhyay et al., 2024), (Hassoun et al., 2023a), (Tracey et al., 2022), (Yu et al., 2022b), (Kalpana et al., 2019), (Bibi et al., 2017)
Sensor	To monitor the operation of food processing (e.g., position, orientation, sorting, cutting, etc.), so as to optimize the operation process.	Inefficient processing flow or techniques (micro)	(Hassoun et al., 2024b), (Hassoun et al., 2022)
	To monitor and evaluate the quality of food during food processing (e.g., color, shape, weight, etc.), so as to optimize processing flow and secondary process low quality food.	Inefficient processing flow or techniques (micro), Failure to meet quality or aesthetic standards (meso)	(Hassoun et al., 2024b)
	To monitor the quality of food (e.g., temperature, gas, pH, biology, etc) through the installation of food packaging.	Poor packaging techniques (micro), Inefficient food quality monitoring (micro)	(Altmann et al., 2023), (Upadhyay et al., 2024), (Gopalakrishnan et al., 2023), (Hassoun et al., 2023a), (Tracey et al., 2022), (Hassoun et al., 2022), (Yu et al., 2022b), (Kalpana et al., 2019), (Chen et al., 2017), (Bibi et al., 2017)
Digital Twin	To simulate the quality change of food during food processing so as to optimize the processing flow.	Inefficient food processing flow (micro)	(Hassoun et al., 2024b)

FWL has a significant impact on the sustainability of the environment, economy, and society (Pinto et al., 2022). Some articles mention the impact of using digital technologies to reduce FWL on the sustainability of FSC, which can be briefly summarized as follows:

(a) Environment: Much literature points out that a large amount of FWL will increase carbon emissions and further aggravate the greenhouse effect (Sharma et al., 2023). To prevent this, the FSC has introduced digital transformation schemes at different stages. At the micro level, precision agriculture optimizes agricultural

Table 8
Retail & distribution phase.

Technology	Application method	FWL event	Publication
Artificial Intelligence	To predict the demand of the food retail market and manage the inventory accordingly, so as to avoid overstock and unsalable food.	Improper inventory management (micro), Inconsistent with market demand (meso)	(Hübner et al., 2024), (Pandey and Mishra, 2024), (Hassoun et al., 2022), (de Souza et al., 2021)
	To predict the marketable period of food based on storage environment and food quality information, so as to make decisions accordingly.	Misjudge food shelf-life or expiration date (micro), Improper inventory management (micro)	(Song et al., 2024), (de Souza et al., 2021)
	To set prices based on food quality information, so as to drive sales demand.	Inefficient sale strategy (meso)	(Yang et al., 2022), (de Souza et al., 2021)
Digital Platform	To improve the dissemination of food retail information, and work as a bridge among supplier, retailer, and consumer, provide more channels and encouragement for food donation, sales, and distribution	Lack of connection among supplier, retailer, and consumer (meso)	(Suali et al., 2024), (Amaral and Orsato, 2023), (Mullick et al., 2021), (Ciulli et al., 2020), (Michelini et al., 2018), (Sewald et al., 2018), (Sharma et al., 2018)
Digital Twin	To optimize the sales and operations planning of food products to predict and detect variabilities across the value chain, as well as to prevent and reallocate food surplus.	Improper inventory management (micro), Inefficient sale strategy (meso), Inconsistent with market demand (meso)	(Sengupta and Dreyer, 2023)
Radio Frequency Identification	To help judge the marketable period of food by tracing the food logistics	Misjudge food shelf-life or expiration date (micro), Improper inventory management (micro)	(Bibi et al., 2017)
Sensor	To monitor the quality of marketable food and make decisions accordingly.	Misjudge food shelf-life or expiration date (micro), Improper inventory management (micro), Inefficient sale strategy (meso)	(Özbilge et al., 2024), (Kayikci et al., 2022a), (Yang et al., 2022), (de Souza et al., 2021)

Table 9
Consumption phase.

Technology	Application method	FWL event	Publication
Artificial Intelligence	To analyze, identify, and classify the content of food leftovers, so as to detect food surplus origin	Misjudge food demand quantity in out-of-home consumption (e.g. public catering) (meso)	(Principato et al., 2023), (Strotmann et al., 2022)
	To predict the food demand quantity, so as to optimize planning accuracy	Misjudge food demand quantity in out-of-home consumption (e.g. public catering) (meso)	(Strotmann et al., 2022)
Digital platform	To optimize, know, and change the dietary behaviour and knowledge (e.g., purchase planning, meal planning, portioning, food saving awareness, etc.) of consumers.	Lack of awareness and methods to tackle food waste (micro), Misjudge food demand quantity (meso)	(Suali et al., 2024), (Principato et al., 2023), (Makov et al., 2023), (Strotmann et al., 2022), (Yu et al., 2022a), (Heidenstrøm and Hebrok, 2022), (Vo-Thanh et al., 2021), (Ciulli et al., 2020)
	To provide channels among consumers to share or give away food that cannot be consumed before expiration.	Lack of connection among consumers (meso)	(Makov et al., 2023), (Strotmann et al., 2022), (Vo-Thanh et al., 2021), (Mazzucchelli et al., 2021), (Sharma et al., 2018), (Michelini et al., 2018)
Image processing	To quantify the volume and characterize the content of food leftovers, so as to detect food surplus origin	Misjudge food demand quantity in out-of-home consumption (e.g. public catering) (meso)	(Principato et al., 2023)
Radio Frequency Identification	To help judge the expiration date and quality of food by tracing the food logistics	Misjudge or neglect food expiration (micro)	(Liegeard and Manning, 2020), (Bibi et al., 2017)
Sensor	To monitor the quality of food to be consumed, so as to avoid the expiration of food to be consumed	Misjudge or neglect food expiration (micro)	(Liegeard and Manning, 2020)
	To monitor the environmental information of food preservation (e.g., temperature, humidity, etc.) and infer the expiration date of food accordingly, so as to make decisions	Improper food preservation conditions (micro)	(Liegeard and Manning, 2020)
Social media	To cultivate and motivate consumers' awareness and behaviour towards reducing food waste	Lack of awareness and methods to tackle food waste (micro)	(Luo et al., 2023), (Jenkins et al., 2022), (Young et al., 2017)

management and reduces food loss by monitoring, collecting, analyzing, sharing, and forecasting agricultural data (Hasan et al., 2024; Zhao et al., 2024a; Rajendran et al., 2024; Rossi et al., 2023); smart storage reduces food loss caused by food deterioration by automatically monitoring storage conditions and the quality of stored items (Zhang et al., 2024; Loisel et al., 2021; Wang et al., 2018); digital processing can improve processing efficiency and food quality by optimizing the processing flow and enhancing the sustainability of food packaging (Hassoun et al., 2023a; Tracey et al., 2022; Jagtap et al., 2021); data-driven retail can reduce the waste caused by food hoarding by improving inventory management, optimizing sales strategy, expanding distribution channels, and forecasting market demand (Özbilge et al., 2024; Amaral and Orsato, 2023; Kayikci et al., 2022a; Sharma et al., 2018); intelligent consumption can analyze consumer preferences, customize food plans, enhance consumer cognition, monitor and judge the food consumption period, and open up food sharing channels (Principato et al., 2023; Heidenstrøm and Hebrok, 2022; Vo-Thanh et al., 2021; Liegeard and Manning, 2020). At the macro level, digital FSC can effectively reduce FWL by improving data management efficiency, increasing supply chain resilience, and promoting coordination (Giganti et al., 2024; Senturk et al., 2023; Ersoy et al., 2022; Annosi et al., 2021).

(b) Economic: Although consistent with the digital transformation schemes mentioned above, some articles focus on the economic benefits brought by reducing FWL. From the perspective of improving income, precision agriculture can improve food output by reducing the loss in agricultural production (Rajendran et al., 2024; Hu et al., 2023); using AI and BD can realize dynamic pricing, flexible sale planning, and increase the sales of food that is about to expire (Yang et al., 2022; de Souza et al., 2021); adopting digital platforms opens up new channels to promote

Table 10
The whole food supply chain.

Technology	Application method	FWL event	Publication
Big data	To integrate, utilize, and analyze a large number of food-related data generated on FSC, so as to estimate the potential correlation between variables, provide a clear understanding and prediction for decision makers, and thus find out and prevent the occurrences of FWL.	Inefficient data information processing, analysis and prediction (macro)	(Hassoun et al., 2024b), (Hassoun et al., 2023a), (Hassoun et al., 2023b), (Cicculo et al., 2022), (Yadav et al., 2022b), (Yu et al., 2022a), (Kayikci et al., 2022a), (Hassoun et al., 2022), (de Souza et al., 2021), (Annosi et al., 2021), (Osinenko et al., 2021), (Kazancoglu et al., 2021a), (Astill et al., 2019)
Blockchain	To make the whole FSC transparent and the food-related information traceable, so as to find out the specific causes of FWL.	Low transparency and traceability of FSC (macro)	(Essien et al., 2024), (Giganti et al., 2024), (Hassoun et al., 2024b), (Hassoun et al., 2023a), (Hasan et al., 2024), (Hassoun et al., 2023b), (Niu et al., 2024), (Yontar, 2023), (Dong et al., 2023), (Yang et al., 2023), (Indap and Tanyas, 2023), (Kumar et al., 2023), (Pakseresht et al., 2023), (Vilas-Boas et al., 2023), (Pandey et al., 2022), (Collart and Canales, 2022), (Li et al., 2023), (Kayikci et al., 2022b), (Yadav et al., 2022b), (Hassoun et al., 2022), (Mangla et al., 2021), (Astill et al., 2019)
	To improve the trust, compliance, and coordination among stakeholders in the FSC, reduce the commercial transactions in intermediate links, increase the security of food-related information, and thus reduce the FWL caused by the inefficiency of the FSC.	Inefficient FSC coordination and management (macro)	(Essien et al., 2024), (Giganti et al., 2024), (Hasan et al., 2024), (Hassoun et al., 2023b), (Niu et al., 2024), (Yontar, 2023), (Dong et al., 2023), (Yang et al., 2023), (Indap and Tanyas, 2023), (Kumar et al., 2023), (Pakseresht et al., 2023), (Vilas-Boas et al., 2023), (Pandey et al., 2022), (Collart and Canales, 2022), (Li et al., 2023), (Kayikci et al., 2022b), (Yadav et al., 2022b), (Hassoun et al., 2022), (Mangla et al., 2021), (Astill et al., 2019)
Cloud Computing	To assist the operation of other digital technologies, store, process, analyze, share and manage a large number of collected food-related data, so as to help decision makers obtain effective information through food-related data to reduce FWL.	Inefficient data information monitoring, sharing and management (macro), Inefficient data information processing, analysis and prediction (macro)	(Hübner et al., 2024), (Yang et al., 2023), (Yadav et al., 2022b), (Yu et al., 2022b), (Hassoun et al., 2022), (Jagtap et al., 2021)
Digital Twin	To simulate and evaluate the quality evolution process of food at each phase of the FSC, capture every change in the whole FSC, and provide real physical data for decision makers to help identify, judge, and predict the potential causes of FWL in the FSC.	Low transparency, traceability and resilience of FSC (macro)	(Sengupta and Dreyer, 2023), (Singh et al., 2023), (Vilas-Boas et al., 2023), (Onwude et al., 2022), (Shrivastava et al., 2022), (Defraeye et al., 2021), (Hassoun et al., 2022), (Shoji et al., 2022), (Defraeye et al., 2019)
Digital Platform	To effectively implement FWL tackling measures based on the widespread application of digital platforms.	Inefficient data information processing, analysis, and prediction (macro)	(Suali et al., 2024), (Ciulli et al., 2020)
	To enhance the connectivity among stakeholders, increase food-related information sharing, simplify the intermediate process, so as to improve the efficiency of FSC.	Low transparency and traceability of FSC (macro), Inefficient FSC coordination and management (macro)	(Suali et al., 2024), (Amaral and Orsato, 2023), (Ciulli et al., 2020)
Radio Frequency Identification	To make the whole FSC transparent and the food-related information traceable, so as to find out the specific causes of FWL and make decisions accordingly.	Low transparency and traceability of FSC (macro)	(Song et al., 2024), (Vilas-Boas et al., 2023), (Yadav et al., 2022b), (Bibi et al., 2017)
Information and Communication Technologies	To increase the connectivity among stakeholders on the FSC by rapidly and frequently acquiring, exchanging, and disseminating large amounts of food-related information, enhancing communication, trade and services among people, organizations and things to achieve efficient FSC management and reduce the occurrences of FWL.	Inefficient data information monitoring, transmission and sharing (macro), Inefficient FSC coordination and management (macro)	(Yadav et al., 2022b), (Ersoy et al., 2022), (Singh et al., 2019)
Internet of Things	To interconnect all digital devices in the FSC to enable the collection, transmission, analysis, and storage of food-related data, providing end-to-end visibility to monitor and understand the state of food throughout the FSC in real time	Inefficient data information monitoring, transmission, sharing and management (macro), Low transparency and traceability of FSC (macro)	(Özbilge et al., 2024), (Aggarwal et al., 2024), (Hassoun et al., 2024b), (Hassoun et al., 2023a), (Hasan et al., 2024), (Senturk et al., 2023), (Hassoun et al., 2023b), (Yang et al., 2023), (Kumar et al., 2023), (Saranya et al., 2023), (Song et al., 2024), (Vilas-Boas et al., 2023), (Yadav et al., 2022b), (Paul et al., 2022), (Kayikci et al., 2022a), (Kim and Lee, 2022), (Yu et al., 2022b), (Hassoun et al., 2022), (Yang et al., 2022), (de Souza et al., 2021), (Jagtap et al., 2021), (Liegeard and Manning, 2020), (Astill et al., 2019), (Bogataj et al., 2017)

food sales (Amaral and Orsato, 2023; Michelini et al., 2018). From the perspective of cost savings AI and sensors are applied: to optimize inventory management and reduce operating costs (Özbilge et al., 2024); leveraging AM to recycle food and improve the utilization rate of resources (Hassoun et al., 2024b). From the perspective of efficiency improvement robot technology improves production and processing efficiency and reduces labor costs and error rates (Hassoun et al., 2024b; Rajendran et al.,

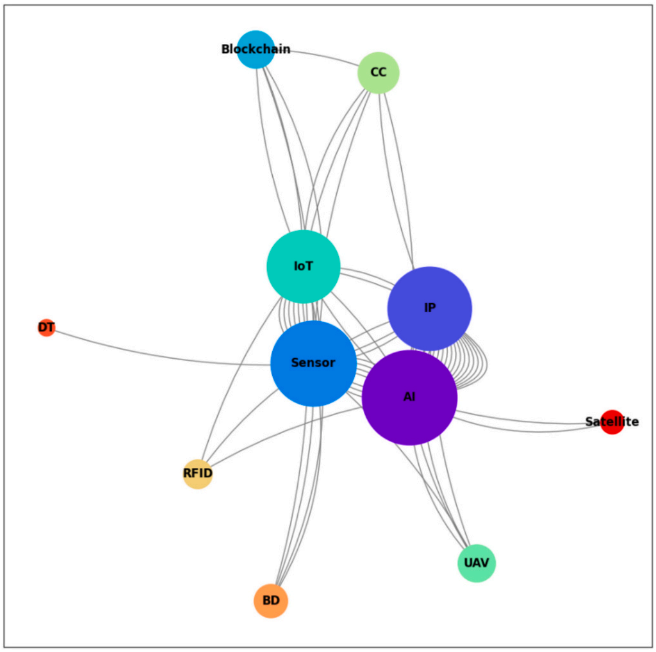

Fig. 6. Network mapping of digital technology collaboration.

2024; Hassoun et al., 2023a); AI, sensors and IP can supervise inventory to reduce food expiration and improve inventory turnover rate (Kayikci et al., 2022a; Yang et al., 2022). From the perspective of risk management, blockchain is adopted to decrease transaction fees and reduce food fraud and wrong transactions (Essien et al., 2024; Giganti et al., 2024; Indap and Tanyas, 2023); AI and BD are integrated to predict market demand and reduce food overproduction (Hassoun et al., 2024b; de Souza et al., 2021). From the perspective of the circular economy, digital technology improves FSC's overall performance, for example blockchain and BD enhance trust among stakeholders, promote cooperation, and digital platforms facilitate the connection between stakeholders (Pakseresht et al., 2023; Kazancoglu et al., 2021a).

(c) Society: With the implementation of the digital transformation scheme as above, some studies have discussed the social welfare brought by reducing FWL. From the perspective of food quality safety, technologies such as AI, sensors, IoT and RFID are deployed to ensure that food is eaten while kept fresh so that more people can obtain food supplies (Kayikci et al., 2022a; Liegeard and Manning, 2020; Shoji et al., 2022; Yang et al., 2022). From the perspective of food sharing and accessibility, the DP is used to disseminate information, improve the accessibility of food, and share food that is about to expire but still edible with people in need (Amaral and Orsato, 2023; Mazzucchelli et al., 2021; Michelini et al., 2018; Sharma et al., 2018). From the perspective of education and awareness-raising, SM and DP are used to teach consumers how to plan their diet, preserve food, reduce food waste, and raise awareness (Heidenstrøm and Hebrok, 2022; Young et al., 2017). In enhancing social cohesion, the DP can connect multiple stakeholders to jointly implement measures to reduce FWL and enhance community cohesion (Ciulli et al., 2020). Blockchain can improve the transparency of FSC, enhance the trust of stakeholders, promote cross-sectoral and cross-industry cooperation, and jointly tackle FWL events (Essien et al., 2024; Giganti et al., 2024; Kayikci et al., 2022b).

4.6. The barriers to digitalization in reducing FWL

Although digitalization has significantly improved the sustainability of FSC and demonstrated its positive effects, the full implementation of digital technology still faces many obstacles - related literature has discussed this issue. Obstacles can be synthesized at a technical, organizational and environmental level as follows:

(a) Technical level: 1. Immaturity of technology. Some technical research is still at the experimental stage. It ignores that the complexity of the real environment will affect performance (Zhang et al., 2024; Senturk et al., 2023; Rajendran et al., 2024). There are some common limitations in the development process, including for example insufficient data sets (Zhao et al., 2024a), poor data quality (Demilie, 2024), poor scalability (Kayikci et al., 2022b). In addition, because of the variety of FWL events and food types, the applicability of one technology is very limited (Giganti et al., 2024; Song et al., 2024; Senturk et al., 2023; Rajendran et al., 2024; Shrivastava et al., 2022; Wang et al., 2018). 2. Technological complexity. The utilization of some technologies requires highly specialized knowledge and skills, which may make implementation and maintenance more difficult (Essien et al., 2024; Li et al., 2023; Singh et al., 2019). 3. Technological integration. The introduction of some technologies usually requires integration with existing systems, but the low interoperability brought by poor infrastructure or inconsistent technical indicators may lead to failed deployment (Giganti et al., 2024; Hasan et al., 2024; Hassoun et al., 2024a; Yadav et al., 2022b; Defraeye et al., 2021).

(b) Organizational level: 1. High investment. The introduction of new technologies usually requires equipment purchase, talent cultivation and management mode changes. This process will be accompanied by a certain degree of risk (Giganti et al., 2024; Shrivastava et al., 2022; Tracey et al., 2022; Liegeard and Manning, 2020). 2. Lack of technological understanding that is showed through stakeholders' lack of understanding, knowledge, and skills in the application of digital technologies (Hassoun et al., 2024a; Kazancoglu et al., 2021a; Annosi et al., 2021; Mangla et al., 2021). 3. Resistance and neglect. Some stakeholders lack trust, neglect, or even resist digital change, which makes it difficult for digital technologies to be widely adopted (Seo and Shigi, 2024; Amaral and Orsato, 2023; Pakseresht et al., 2023; Singh et al., 2019). 4. Insufficient trust among stakeholders. A number of stakeholders are unwilling to cooperate and share information on digitalization, fearing that they will be exploited by competitors (Essien et al., 2024; Kazancoglu et al., 2021a; Annosi et al., 2021).

(c) Environmental level: 1. Data security and privacy. The digitalization of FSC will be accompanied by the generation, transmission, storage, and processing of relevant data, which contains a large amount of personal or sensitive information. There is a risk of this being stolen (Hasan et al., 2024; Pandey and Mishra, 2024; Song et al., 2024; Yang et al., 2023). 2. Lack of regulatory framework. Due to imperfect regulations and laws, stakeholders are likely to face compliance risks, decision-making difficulties, and inadequate trust in the process of digitalization, thus increasing uncertainty (Wu and Tai, 2024; Giganti et al., 2024; Defraeye et al., 2021; Kalpana et al., 2019).

5. Framework development

Based on our findings, this study illustrates the role and relationship of digital technologies in reducing FWL within the FSC (Fig. 7) and further proposes a digital FWL network management framework, as

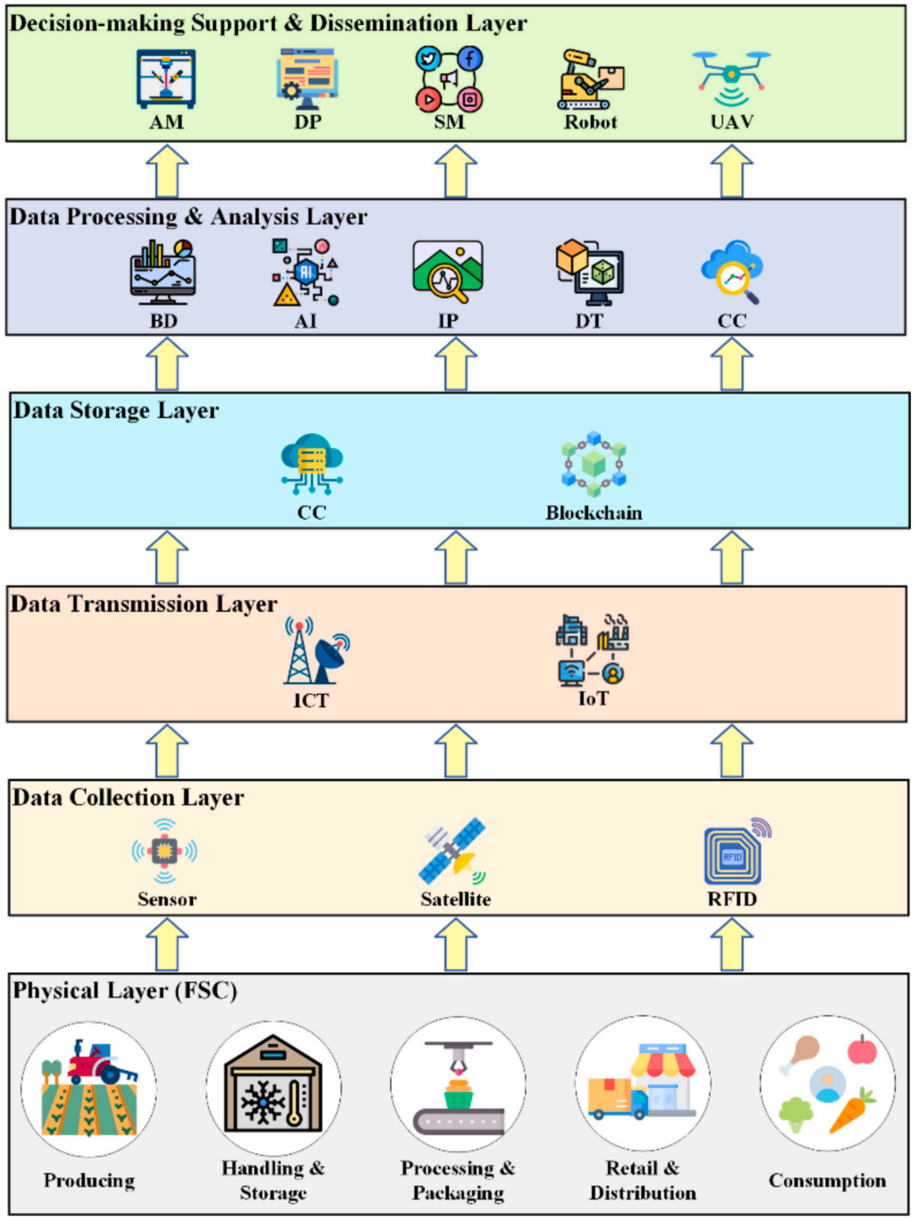

Fig. 7. An architecture regarding the role and relationship of digital technologies in reducing FWL within FSC.

shown in Fig. 8. This hybrid framework is inspired by the seminal work of Chauhan et al. (2021) - a hybrid framework developed through combining the Kipling method (5W1H: why, what, where, when, who, and how) (Hart, 2002) and SKS (Stop, Keep doing, Start) process feedback model (DeLong, 2011). This framework methodically identifies the key aspects of tackling FWL events: "Who" are the actors involved, "how" the events are addressed, "where" actions are taken, "when" deployments occur, "what" the FWL events are, and "why" these events are targeted. The Kipling method, known for its structured approach, enhances understanding and planning (Reid and Smyth-Renshaw, 2012). It is widely applied in various fields (e.g. project management, medical management, supply chain management) for problem identification (Akyol et al., 2020; Børve et al., 2017). However, given that FWL events are dynamic and change even within the same FSC due to various factors (e.g. environment, policy, trade), the Kipling method's static nature is supplemented by the SKS process feedback model. This model, conceptualized for feedback collection and categorization (DeLong, 2011), addresses the variability of FWL.

In our study we employ the Kipling method to delineate the application process of digital technologies in various FSC phases (Fig. 8). "Why" identifies the drivers (social, environmental, and economic) behind addressing FWL events. "Who" categorizes the actors involved in applying digital technologies; primary actors such as producers, manufacturers, retailers, consumers; and secondary actors such as policymakers, governments, NGOs (Djekic et al., 2021). "What" specifies the causes or events of FWL, as detailed in our study. "How" outlines the specific application methods of the 16 digital technologies identified in our research. The responses to "How" and "Who" aim to address "What," influencing social, environmental, and economic aspects. "When" and "Where" relate to the timing and location (FSC phases) of technology application. As the FSC evolves, "feedback" guides actors to "stop" ineffective methods, "keep" successful applications, and "start" new strategies.

6. Discussion

Based on the findings and results presented in Section 5, a critical discussion will be presented in this section. A comparison with previous

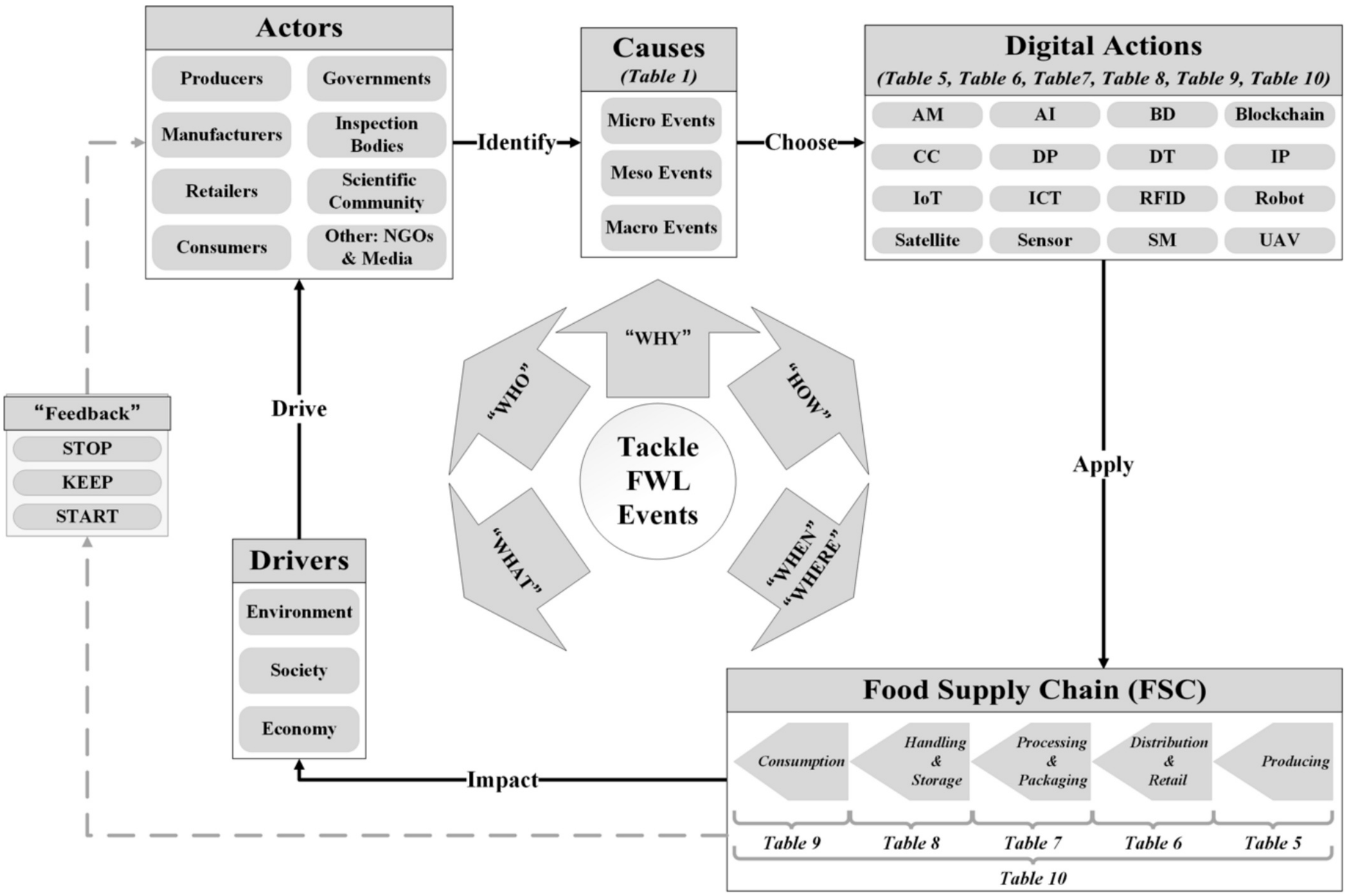

Fig. 8. Digital food waste and loss network management framework.

similar thematic literature, as well as the theoretical and practical contributions, will also be elaborated.

6.1. Interpretation of findings and future directions

6.1.1. The current research trend of digitalization in reducing FWL within the FSC

It can be predicted that the digitalization of the FSC will remain a prominent theme in academic research. The application of digital technology in the complex FWL scene of the FSC is still in its infancy. The application of these technologies needs further development, and more experimental research is needed to improve technical maturity and performance. Moreover the differences in the frequency of the use of digital technologies in the studies reviewed show that academic circles are increasingly interested in specific digital technologies, especially AI, sensors, and IP. This reflects that the current digital application research on FWL events focuses mainly on a few specific digital technologies. Although this makes the development and application of these technologies in FWL more mature, it also limits the exploration of other potential technologies. At the same time, the collaboration between digital technologies mainly focuses on AI and IP, and between AI and sensors. This solidifies combination mode results in that most of the research is limited to a few FWL events, while some potential technical combinations, such as metaverse and AI (An et al., 2025), blockchain and AI, are still in the theoretical stage. Therefore, we call on scholars to jump out of the existing framework, expand the scope of research, and deeply explore a wider range of digital technologies and their combination possibilities. Simultaneously, it is also of great significance to establish governance mechanisms that harness digital practices to foster innovation aimed at reducing FWL within the FSC.

At present, the research on the application of digital technology is mainly to provide tools to help stakeholders reduce FWL. However, this requires the subjective acceptance and cooperation of all parties. In reality, due to the limitations of the environment and resources, many stakeholders have not adopted these feasible solutions. Therefore, we recommend that researchers explore how to formulate policy interventions to influence and change the subjective attitude of stakeholders in the future, rather than simply undertake publicity and education, to achieve more effective nudges.

6.1.2. The negative impact of digitalization on the sustainability of the FSC

Digital technology has played an active role in reducing FWL and facilitating the sustainability of the FSC. However, the application of digital technology is a double-edged sword, which also has negative effects on the environment, economy, and society. On the environmental level, for example, a large amount of computing power is required for blockchain operation, that is "mining," with the consumption of a lot of electricity resulting in increased carbon emissions and increased environmental pressure. According to statistics, the electricity consumption of bitcoin mining may exceed the total energy consumption of some countries. Moreover, due to the short life cycle of mining equipment, it often needs to be replaced, which leads to a large amount of electronic waste (Li et al., 2019). On the economic level, food fraud often occurs on some e-commerce websites, such as selling inferior or expired food and

Table 11
Comparative synthesis of this study and previous reviews.

Item	This study	(Trevisan and Formentini, 2023)	(Yadav et al., 2022b)
Research goal	This paper seeks to identify and synthesize the specific applications of state-of-the-art digital technologies to various FWL events in each FSC stage, accordingly propose a digital FWL management framework, and investigate the implications, obstacles, and potential of these digital technologies	This paper aims to analyze the latest trends of digital technology adoption in agri-FSC, and provide a research agenda to guide future research on the use of digital technology to prevent and reduce FWL	This paper aims to identify the application of Industry 4.0 technology in agri-FSC, including IoT, blockchain, BD, ICT, CC, and network physical systems.
Research methodology	SLR	SLR	SLR
Research scope	As well as considering traditional FWL, it also involves any loss in the primary production process. Focus on how specific digital solutions match a variety of FWL events in the six stages of FSC	From the perspective of the supply chain, it is expected to develop a comprehensive understanding of the implementation of digital solutions throughout agri-FSC, including the contributions of external stakeholders such as charities, food banks, and policymakers	Cover the current status, application areas, adoption approaches, and research challenges of implementing various Industry 4.0 technologies in the agri-FSC.
Research contributions	1. Review, synthesize, and match the applications of digital technologies and FWL events within the whole FSC 2. Develop a digital FWL waste management framework to guide researchers and practitioners in better choosing and exploring the applications of digital technologies 3. Analyze the current research trend of digital technologies and highlight the potential of collaborations among digital technologies 4. Explore the sustainability of digital technologies in reducing FWL within FSC and indicate the negative impact of digital technologies 5. Identify the major barriers to implementing digital technologies in the FSC and suggest future directions	1. Develop a framework to summarize and analyze the functional characteristics and adoption of industry 4.0 technology in reducing FWL around research design, digital technologies, contextual differences, governance, and sustainability 2. Propose a corresponding research agenda, focusing on research design, digital technologies and FWL, context information, governance processes, and sustainability.	1. Review a wide range of 4.0 technologies in FSC 2. Classify the literature based on industry, technology, research approach, country, and publication year 3. Identify the major research dimensions in which these technologies have been applied 4. Put forward suggestions for the future research direction of each technology.

false propaganda, which not only causes economic and health damage to consumers but also weakens consumer trust. In addition, the investment of enterprises to prevent and deal with food fraud activities may lead to the failure of resource allocation (Lee et al., 2022). At the social level, AI prediction may lead to overoptimization of food production, thus reducing food diversity and limiting consumer choices (Galaz et al., 2021).

Apart from the negative impact on the above single level, in practice digitalization may lead to negative consequences which transcend the individual economic, social, and environmental dimensions. For example, digitalization in the pursuit of 'zero resource waste' often over-optimizes supply chain efficiency, which can lead to food surpluses being ignored or reduced. This triggers the 'Lean Paradox', where the pursuit of extreme efficiency optimization of the economic dimension may be achieved while neglecting social and environmental dimensions, especially with regard to food redistribution (Trevisan et al., 2024). Furthermore, digitalization may aggravate the power imbalance in FSC particularly by controlling data and technical resources. Large enterprises can dominate information flow and decision-making, thus limiting the participation opportunities of small farms and suppliers and intensifying unfair competition (Trevisan et al., 2024). Therefore, while discussing how to use digital technology to reduce food waste, future research should also consider avoiding or alleviating these possible negative effects.

6.1.3. *The navigation for overcoming barriers*

To effectively overcome the challenges of deploying digital technology to reduce FWL, a top-down strategy is required. Policymakers should play a leading role in building a comprehensive and reasonable regulatory framework, and in formulating policies to prevent negative effects (such as large-scale unemployment and technology costs) which might result from digitalization, and in eliminating doubts or resentments of lower-level stakeholders because of uncertainty or interest damage. At the same time, they also need to consider how to enhance stakeholder awareness of digitalization, and encourage all parties to work together to build a good digital FWL management system. On the other hand, specific digital technology deployment should follow a bottom-up technology integration strategy. As shown in Fig. 7, some basic digital technologies, such as IoT and sensors, should be deployed in advance to provide the necessary foundation for the subsequent integration of digital technologies. Therefore, future research should be explored from multiple perspectives, including how to evaluate and optimize the implementation effect of digital-related strategies, how to measure and improve the process and performance of digital transformation, and how to effectively cultivate the digital skills of relevant personnel.

6.2. *Comparative and complementary perspectives on prior reviews*

To position this study's contributions within the broader research context, two closely related SLR studies - Trevisan and Formentini (2023) and Yadav et al. (2022b) - are reviewed. Table 11 provides a concise comparative summary of these studies, highlighting both the overlaps and distinctive differences, and illustrating how our analysis complements and expands on their findings.

While all three reviews adopt an SLR methodology, our research deepens this approach by linking digital technology with specific FWL events across every stage of the FSC. By explicitly integrating primary production, we have broadened the traditional scope, thereby capturing potential FWL issues throughout the entire supply chain. In this process, we examine not only how digital solutions can mitigate FWL in the conventional downstream stages but also address the often-overlooked upstream agricultural processes. Moreover, we enrich the existing literature by analyzing both the positive outcomes and the potential adverse effects of digital technology on sustainable development. Specifically, while digital technology contributes positively to reducing

FWL, it may also present challenges such as increased energy consumption, data privacy concerns, and socio-economic disparities. Finally, we identify the main obstacles to the deployment of these technologies, such as technical infrastructure gaps and policy restrictions, in order to propose more detailed intervention measures. Through these contributions, our study not only aligns with previous research but also substantially extends and refines it, offering a broader and more nuanced perspective on the transformative role of digital innovation in reducing FWL.

6.3. Theoretical contributions

This study has significant theoretical implications for the field of FWL and digitalization within the FSC. First, by conducting a thorough statistical analysis and discussion of annual publication volumes, subject areas, research methodologies, and technical research domains, our study sheds new light on the state of the art of research concerning the application of digitalization in addressing FWL. Second, this study addresses the previous fragmentation by integrating the application of various digital technologies to FWL events within the FSC from a unified and comprehensive perspective. Our approach fills existing gaps in academic research and draws attention to areas previously underexplored in the literature. Third, based on the SLR results, this research develops a digital FWL management framework, which provides researchers with a mind map for developing more new digital solutions to reduce FWL. Lastly, this study analyzes and discusses the technical research trends, considers the positive and negative effects of digitalization on the sustainability of the FSC, summarizes the obstacles which may be encountered when deploying digital technologies to reduce FWL, and recommends future research directions.

6.4. Practical contributions

This study makes a significant practical contribution by offering new insights and guidelines for practitioners and stakeholders across all phases of the FSC. Integrating the application methods of digital technologies with corresponding FWL events provides new insights and guidelines for practitioners and other stakeholders from every FSC phase, enabling them to better apply digital technologies to tackle complex FWL events within the FSC. Simultaneously, we develop a digital FWL network management framework to aid in managing the complex changes in FWL events brought about by FSC's dynamics. This framework provides a detailed process description and a roadmap for the application of digital technologies. Our findings could be adopted by all food-related organizations in the FSC to more efficiently reduce the negative social, environmental and economic impacts brought about by FWL (Halloran et al., 2014). In addition, our discussion on the negative impact of digitalization plays a warning role for practitioners. The proposed strategy to overcome the obstacles of digital reduction of FWL is also of guiding value to practitioners.

In the pursuit of a sustainable FSC, recent research emphasizes the need for comprehensive and systematic digital strategies that consider the entire FSC as the deployment unit (Margaritis et al., 2022). Our research contributes to this goal by expanding the understanding of how digital technologies can be integrated and applied within the FSC. This not only motivates further exploration into the future development of digitalization but also paves the way for driving digital transformation in the food industry (Zhong et al., 2017).

Appendix A

7. Conclusions and recommendations for future work

This SLR critically examines recent research on the application of digitalization in addressing complex FWL events within the FSC. Our study uniquely integrates a diverse range of digital technologies, moving beyond the common single-technology focus seen in much of the current FWL research (e.g. Blockchain, IoT, AI, Big Data) (Giganti et al., 2024; Ahmadzadeh et al., 2023; Pandey and Mishra, 2024; Margaritis et al., 2022). In this paper, we adopt a comprehensive and unified perspective - this research analyses the application of 16 different new digital technologies across key FWL events in various FSC deployment phases. Consequently, this research contributes significantly to the establishment of a knowledge framework for applying digitalization to complex FWL events in the FSC. Moreover, to address the complexity of FWL events within the dynamic FSC, we develop a digital FWL management network framework for tackling FWL using emergent technologies, offering a practical outlook for managers and different actors in the FSC. Finally, we deeply analyze the research trend, sustainable impact, and deployment obstacles of digital technologies in reducing FWL and propose future research directions accordingly.

The limitations of this study are threefold. First, our review focused exclusively on English-language literature, which may have omitted relevant studies published in other languages. Second, we included only journal articles, although influential ideas related to digitalization in the FSC have also been developed in key reports and books. For example, Pinstrup-Andersen et al. (1999) noted that ICT could be used to reduce agricultural losses, and the FAO's Digital Agricultural Revolution report marked a significant milestone for food security (Trendov et al., 2019). Third, we applied publication year and SJR impact factor as screening criteria to reduce the initial 13,438 papers to a manageable sample size. Although these criteria help ensure a certain level of quality and relevance, they may inadvertently exclude potentially important research, particularly from emerging journals that have not yet achieved high SJR rankings. Ideally, a more comprehensive approach would include a broader range of sources to obtain a more holistic view of the literature.

It is recommended that future research builds on the directions proposed in Section 6.1. Additionally, quantitative text mining techniques (e.g., Latent Dirichlet Allocation) could be used to supplement qualitative SLR, enabling the processing of a significantly larger number of articles without the need for strict screening criteria. This approach would help capture the evolving digital landscape of the FSC more comprehensively and reduce potential bias introduced by current filtering methods. Moreover, incorporating insights from FSC stakeholders can provide valuable guidance for further exploring new applications, processes, management frameworks, and organizational structures to address FWL problems through digitalization.

CRediT authorship contribution statement

Hongda An: Writing – original draft, Methodology, Formal analysis, Data curation. **Carlos Galera-Zarco:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

We have no known conflict of interest to disclose.

Table 12
Extraction table.

Category	Item	Description
Basic information	Author	People who wrote this document
	Document title	Name of this document
	Year	Year this document was published
	Source	Name of the journal that published this document
	SJR impact factor	SJR impact factor of the journal that published this document
Research Design	Methodology	Quantitative, qualitative, mixed method, review, technical development, conceptual/theoretical
Findings	Phase	Phase of food supply chain
	Digital technology	The types of digital technologies used in the research
	Corresponding FWL event	The causes of FWL in the research
	Solution	The application method of digital technologies in the research
	Barriers	The reasons why digital technologies cannot be implemented in practice normally
	Sustainability	The impacts on the environment, economy, and society

Appendix B

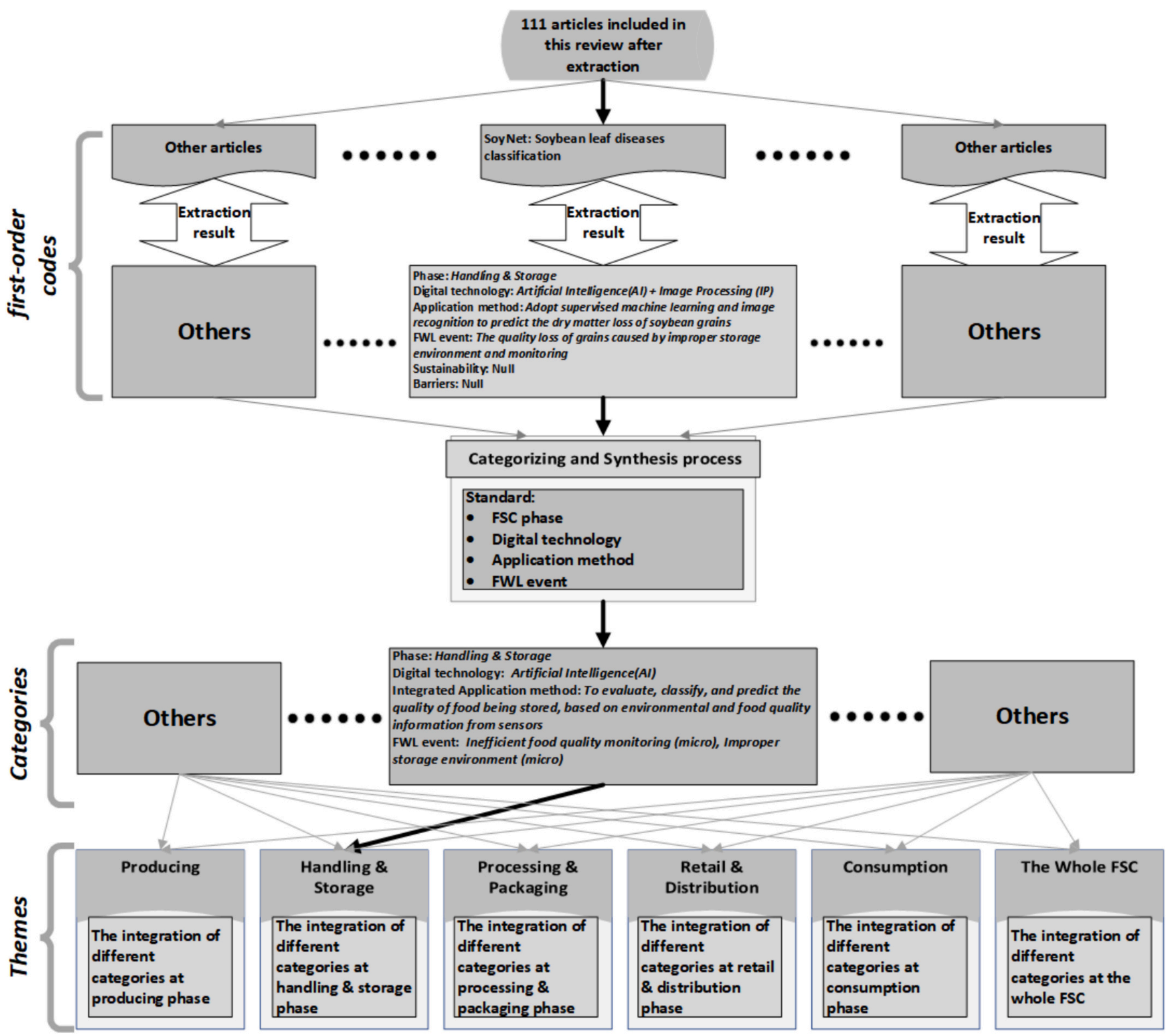

Fig. 9. An example of the synthesis process for Karlekar and Seal (2020)'s article.

Data availability

Data will be made available on request.

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