Digital Technologies for Food Loss and Waste Prevention and Reduction in Agri-Food Supply Chains: A Systematic Literature Review and Research Agenda

Caterina Trevisan and Marco Formentini

***Abstract*—Despite the benefits resulting from the use of Industry 4.0 technologies in the agri-food sector, the adoption of digital technologies for preventing and/or reducing food loss and waste (FLW) across the agri-food supply chain is still under investigation. In fact, enhancing and optimizing agri-food supply chain operations through digital technologies would just represent a partial effort if FLW prevention and reduction are not effectively addressed. Although companies are starting to adopt digital technologies for eliminating FLW from their operations, the implementation process and the achieved results are generally presented at a superficial level and practical guidance is still missing. This systematic literature review contributes to theory by developing a framework analyzing the state-of-the-art of adoption of each Industry 4.0 technology across the agri-food supply chain, and providing a research agenda structured around the main themes of research design, digital technologies, contextual differences, governance, and sustainability. Eventually, the study also informs managers in the agri-food industry about the potential implementation of digital technologies for preventing and reducing FLW in across the agri-food supply chain.**

***Index Terms*—Agri-food supply chain (AFSC), digital technologies, digitalization, food loss and waste (FLW), industry 4.0.**

Nomenclature

List of Abbreviations

AFSC	Agri-food supply chain.
AI	Artificial intelligence.
BDA	Big data analytics.
CRM	Customer relationship management.
DT	Digital technologies.
EIS	Enterprise information system.
ERP	Enterprise resource planning.
FLW	Food loss and waste.
FW	Food waste.
GPS	Global positioning system.
ICT	Information and communication technology.
IoT	Internet of Things.
ML	Machine learning.
PLM	Product lifecycle management.
RFID	Radio-frequency identification.
RPA	Robotic process automation.
SLR	Systematic literature review.
WMS	Warehouse management system.

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The authors are with the Department of Information Engineering and Computer Science, University of Trento, 38123 Povo, Italy (e-mail: caterina.trevisan-1@unitn.it; marco.formentini@unitn.it).

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I. Introduction

As a growing number of people is facing food insecurity and the global food systems have been severely tested by a combination of health crisis, climate-related issues, and conflicts, still too much food is lost or wasted throughout the AFSC. Between 25% and 50% of food produced does not reach the consumers, with the majority of losses occurring from the producers to the retailers point in the supply chain [1]. Wasting food has significant negative consequences on social, economic, and environmental sustainability: wasted food in landfills generates about 8%–10% of global greenhouse gas emissions [2], not to mention blue water footprint, land footprint, and biodiversity reduction [3]. Moreover, it leads to an economic cost of around 143 billion euros per year in the 28 European countries alone [4]. Halving per capita global food waste by 2030 is the objective of target 12.3 of UN sustainable development goal [5]; thus, reducing FLW represents a relevant and timely issue.

Several strategies of reducing FLW have been identified, depending also on the supply chain stages considered [6]. Despoudi [1] individuates the adoption of technology as one key aspect for food loss reduction, especially in the upstream part of the supply chain. For instance, Industry 4.0 (I4.0) solutions, such as blockchain or IoT, allow the monitoring of the ambient conditions of food products from the harvest until the selling stage, thus detecting their deterioration stage and improving the operations along the entire AFSC [7], [8], [9]. Even in the downstream supply chain stages (i.e., consumption, food service, and food sharing), digital technologies are frequently adopted to avoid or reduce food waste, such as digital platforms

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for redistributing food surplus at a lower price for consumers or for free to charities helping people in need [10], [11].

The adoption of I4.0 digital technologies, coupled with the ability of capturing novel insights from the amount of data collected, is recognized as a key factor to realize more efficient, resilient, and sustainable food systems [12], [13], [14]. However, despite the recognized importance of I4.0 in the agri-food sector, the application of digital technologies for achieving FLW prevention and reduction goal is still under investigation. Indeed, the literature outlines that the majority of efforts and investments in digitalization of the AFSCs are directed toward production process innovation and optimization through smart agriculture [15] and precision farming [14], [16], [17] or for enhancing food logistics management through solutions, such as robotics and automation, drones, IoT, and AI [18], [19], [20], [21]. Nevertheless, increasing and optimizing food production and delivery through digital technologies would represent just a partial effort if FLW prevention and reduction are not effectively addressed [17], [22]. However, despite the availability of some industry cases, such as the case of Walmart seeking to eliminate food waste from its operations [23] and of several other companies adopting digital technologies for reducing FLW [24], [25], the results achieved by such companies are generally presented at a superficial level and practical guidance on the implementation of digital technologies for FLW prevention and reduction is still missing, thus precluding generalizability of the findings. Moreover, the available studies and practical cases often present a limited and fragmented perspective on the supply chain, frequently considering each supply chain actor separately, and focusing especially on the downstream food supply chain [26], thus lacking an integrated perspective on digital technologies adoption across all stages of the supply chain [27].

Therefore, the objective of this study is twofold. First, we will provide a comprehensive review of the literature on the digital technologies used to reduce FLW in AFSCs. Second, we will identify future research opportunities and gaps by defining a research agenda. To achieve these two objectives, we pose the following research questions.

RQ1: What is the state of the art of the literature on digital technologies for preventing and/or reducing FLW across the entire AFSC?

RQ2: How do digital technologies contribute to achieve the FLW reduction and/or prevention goals across the AFSC?

Our study contributes to the literature on the adoption of digital technologies across the AFSC for preventing and/or reducing FLW by extending the previous literature reviews, i.e., developing a framework and proposing an agenda for future research. The developed framework aims at capturing the adoption of each technology across each supply chain stage and it provides a basis to inform managers in the agri-food industry about the potential implementation of digital technologies for preventing and reducing FLW across the AFSC and related key implications.

The article is organized as follows. Section II provides a theoretical positioning of the topic and the main definitions. Section III presents the research questions and methodology. Section IV reports the framework of analysis and provides a bibliometric overview of the results. Section V discusses the results and provides a research agenda. Contributions are presented in Section VI and conclusions and limitations are given in Section VII.

II. Theoretical Positioning

First, we provide an overview of the impact that digital technologies characterizing the Industry 4.0 phenomenon have on economic, social, and environmental sustainability. Second, we review the adoption of digital technologies in AFSCs and highlight the key limitations and constraints in preventing and reducing FLW.

A. Impact of Industry 4.0 Technologies on Sustainability

The Industry 4.0 phenomenon was initially characterized by nine technological pillars, or "enabling technologies": robotics and automation, big data, simulation, system integration, IoT, cybersecurity, the cloud, additive manufacturing, and augmented reality [28]. In addition to these nine technologies, the recent paper by Zekhnini et al. [29] integrates a supply chain perspective and suggests adding the most discussed technologies in Supply Chain Management 4.0: BDA, blockchain, AI, and IoT. In addition to the widely shared benefits that digital technologies have for firms' and supply chain performance, the technologies of Industry 4.0 represent an opportunity to promote sustainable and circular practices throughout the entire supply chain and [30], enabling sustainable AFSCs [14], [31] and sustainable manufacturing [32]. For instance, developing BDA capabilities could enable the manufacturing industry to apply sustainable practices more efficiently [33]. BDA can also provide more realistic and timely sales forecasts, in line with customer's expectations, leading to the reduction of stocks and waste and, in turn, saving energy and resources [34]. Therefore, BDA is an essential capability for enabling sustainable supply chain management, providing benefits in all three dimensions of sustainability [35]. IoT also plays a central role in digital transformation across various industries, as it provides performance monitoring and optimized productivity [36], enabling proactive maintenance with positive results in reducing defective products [37]. IoT helps, in turn, organizations save costs by reducing wastes of energy [38]. Moreover, technologies such as blockchain, sensors, and satellite image processing enhance social and environmental audits, positively contributing to the supply chain sustainability performance [39].

In general, Industry 4.0 represents an opportunity for the entire supply chain to engage in sustainable value creation, in line with the three sustainability dimensions (i.e., social, economic, and environmental). Indeed, it enables new data-driven business models, promoting sustainable product development processes, and inspiring organizations to adopt resource-efficient practices, ultimately offering the opportunity for realizing closed-loop product life cycles and industrial symbiosis [40].

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B. Digital Technologies in Agri-Food Supply Chains

The adoption of digital technologies in the AFSC is not novel. In this article, we define adoption as the intentional implementation and usage of a given digital technology for performing a series of activities within a company's operations in one or more stages of the supply chain. The word "adoption" is the term that most frequently appears in the literature on the adoption of digital technologies across the AFSC for preventing and/or reducing FLW (e.g., Annosi et al. [27], Ciccullo et al. [41], Kamble et al. [42], Kazancoglu et al. [43]). As already pointed out by Demartini et al. [36], food companies are slowly keeping pace with the digital transformation occurring in other sectors, and mainly with the aim of creating more secure AFSCs. However, the adoption of digital technologies in the AFSC is more complex compared to other industries since AFSC are more vulnerable to deterioration and perishability in comparison with other products [43] and are subjected to heavy regulations [44]. Lezoche et al. [45] identify four main sources of contextual uncertainty in the AFSC: product (shelf-life, deterioration rate, lack of homogeneity, food quality, and food safety), process (harvesting yield, supply lead time, resource needs, and production), market (demand and market prices), and environment (weather, pests and diseases, and regulations). For instance, ICT tools used in the fresh fruits and vegetables sector are the same as for other goods; however, these supply chains experience short lifetimes and fragile commodities [46] because inventory turnarounds are faster, under cold chain conditions, and handling operations are more delicate to avoid damage [47]. In this context, the proper implementation of digital technologies has an enormous impact in managing those uncertainties by allowing for better monitoring of food products and processing, increased efficiency, sustainability, flexibility, agility, and resilience along the whole supply chain from the farmers to the final customers. Applying digital technologies to existing operations demands a greater technological and economic effort, but it is even more crucial for creating a more sustainable supply chain. Similarly, managing closed loop supply chains implies to cope with higher uncertainties and complexity. Adopting circular economy principles requires enhanced information traceability, data availability and security, as well as close collaboration between other supply chain actors and stakeholders [43].

Despite these critical aspects, a number of real cases of implementation exist, thus proving the interest in digital technologies is growing in the agri-food sector. Moving upstream in the supply chain, various applications of digital technologies are pushing traditional agricultural practices towards smart farming [31], underlining a growing interest among practitioners in AFSC digitalization in several processes, such as measuring the environmental parameters of soil through IoT or monitoring the fields by analyzing real-time satellite images, both of which generate a massive amount of data that requires adequate data analytics capabilities.

The academic literature deals with the topic of FLW prevention and/or reduction through digital technologies across AFSC in different ways. For instance, Lezoche et al. [45] analyze impacts and challenges of the most diffused digital technologies in the agricultural sector, focusing on industrial farming, and Lioutas et al. [48] weight potential benefits and perils of the adoption of digital farming technologies. Traceability is the top concept addressed by most of the authors dealing with digitalization along food chains [49], which typically leverage on blockchain technologies for tracking goods [9], [25], [50], [51].

C. How Can Digital Technologies Contribute to FLW Prevention and Reduction?

Several definitions of FLW exist [52], [53], [54]; in this article, we adopt the definition provided by Cattaneo et al. [55], [56], defining FLW as the decrease in quantity or quality of food along the AFSC. Food losses can occur along the supply chain, from harvest up to the moment it enters a store, while food waste occurs at the retail and consumption levels.

Considering the review performed by Amentae and Gebresenbet [49], the concept of reducing FLW through digital technologies emerged in a substantial number of papers, but it received minor attention with respect to other themes such as traceability, sustainability, and further AFSC performance issues. Even fewer publications exist directly addressing the application of digital technologies for FLW prevention and/or reduction. A branch of studies focuses on identifying and addressing FLW root causes [57], and other studies concentrate on how collaboration among stakeholders can reduce FLW along the entire supply chain [58], [59].

Only a few publications stand out for a more comprehensive view of the topic: Annosi et al. [27] adopt a multiple case-study approach and in-depth interviews to explore how technologies are used to prevent food waste throughout the food supply chain and within a company's boundaries. Ciccullo et al. [41] investigate the role of technological solutions on food waste reduction and unfold how collaborations with supply chain actors and technology providers can facilitate the effectiveness of the technologies in reaching FLW objectives. Still, the vast majority of research focuses only on a restricted portion of the food supply chain (i.e., retail, food and catering services, or households) [60], [61]. Other studies consider just a specific technology or food category, such as fruits and vegetables products [41] or provide single case studies, thus remaining at an exploratory level.

Moreover, applications of digital technologies to FLW issue and related scientific publications are mainly concentrated in developed countries; however, even in more advanced technological contexts, there are still many challenges hindering the practical implementation of such innovative solutions [62]. Yet, a few remarkable practical examples and case studies from particularly innovative firms helps shed light on the growing sensibility of practitioners towards the digitalization of agri-food industry and of its positive impact on FLW minimization. The first example of such a firm is the multinational Walmart, who committed to eliminate waste of all kinds, from reducing in-store packaging waste to eliminating food waste from operations, in operations in the U.S., Canada, Japan, and U.K. [23]. In line with the food waste reduction goal, digital technologies were introduced to improve the manual inspection process of food from farm to fork. Indeed, since 2017, Walmart relies on the machine learning algorithm "Eden" that scans products to assess quality and freshness, resulting in $86M of savings from food waste reduction due to lower screening times and in-store prioritization. Further improvements of the algorithm are planned by adding sensors to monitor temperature and light conditions of shipments.

A second example comes from the Italian firm Barilla that demonstrated a strong commitment to measuring, monitoring, and reducing FLW in its processes by integrating the values of sustainability and loss reduction into its business model. Formentini et al. [63] analyzed the entire lifecycle of Barilla's soft wheat bread, measuring the waste generated in each supply chain stage and the main causes of waste. These data increased the company's awareness about the circularity level of the product's value chain, enabling management to follow the right strategy for FLW reduction and valorization.

Although the relevance of the FLW issue is recognized and shared among scholars and practitioners, and the diffusion of digital technologies in the agri-food sector is growing, the literature about the topic is still limited and lacks a full supply chain perspective. This literature review aims to fill this gap by analyzing the existing literature according to a framework developed by the authors. More precisely, the objective of this study is to investigate the current literature on digital technologies used to address FLW reduction and prevention in AFSC and thus provide a roadmap for future research.

III. Research Design

The aim of this study is to inform both scholars and practitioners on the state of the art of digital solutions to address FLW issue across the entire agri-food system. As Annosi et al. [27] highlight, a limited number of papers on FLW adopted a supply chain perspective, which requires moving from an actor-centric approach to a wider process view. This finding is in contrast to what already expressed by the European Commission's directive on waste,[1] calling for the adoption of FLW preventive measures in all stages of the supply chain, including restaurants, food services, and households. Indeed, limiting the scope of analysis to single actors in the supply chain leads to partial and incomplete considerations. To overcome this limitation, we are adopting a supply chain perspective to develop an integrated understanding of the implementation of specific digital solutions throughout the supply chain. In addition, we are including in our analysis the contribution of external stakeholders since supply chain circularity and sustainable FLW management require the collaboration of multistakeholders and businesses [64], such as charities, food banks, and policymakers.

A. Material and Methods

The literature on the application of digital technologies to FLW reduction and management is still limited and fragmented, thus we adopted a SLR approach to offer a methodical and comprehensive view of the topic [65]. The chosen methodology is proven to be the most accurate, efficient, and high quality for identifying and evaluating extensive bodies of the literature [66]. An SLR is well suited for investigating a topic across different fields [67], which stays at the interface of many different disciplines, such as supply chain management, innovation, computer science, and environmental and social sustainability. We adopted the five-step process suggested by Denyer and Tranfield [65] to ensure the review transparency, as well as inclusivity and explanatory principles, which we combined with a PRISMA checklist and flow diagram for clearly reporting the number of studies reviewed [68] (Fig. 1).

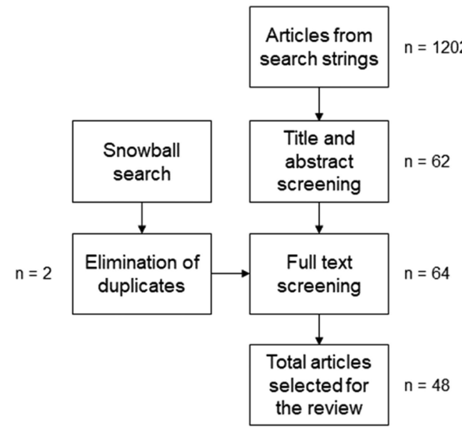

Fig. 1. Summary diagram of the systematic selection process.

The first step is defining the scope of the review by assessing the relevance and size of the literature [69]. Analyzing the number of scientific publications in Scopus database over time as a result of the combination of keywords: "Industry 4.0" AND "Food" OR "Food Industry," we saw that coverage of Industry 4.0 started to gain relevance in food industry related literature since 2015. Therefore, after identifying the temporal boundaries of the research, we identified meaningful keywords and search terms to retrieve the core contributions. Major bibliographic databases were used to search for related articles, such as those provided by the major publishers, Elsevier, Emerald, Springer, Wiley, adopting Scopus search engines. Keywords were selected through brainstorming sessions among the author team and combined using logical operators "AND" and "OR" within article title, abstract, and keywords. A first set of 1202 articles was retrieved in January 2023 using the keywords search available in the Appendix. Each article's overlap with the research topic was checked through the examination of the title and abstract of each article retrieved. Moreover, articles published in journals not dealing with the subject areas of supply chain and operations management, food and agriculture management and computer science and digital transformation were excluded, as reported in the search query. Articles not directly dealing with Industry 4.0 digital technologies specifically used for the scope of preventing and/or reducing FLW along the supply chain were excluded. We noticed that only a few studies explore the use of digital technologies specifically for FLW management throughout the food supply chain; therefore, such a process left us with 62 articles. Furthermore, snowball search was used in order to refine the searches and, after the elimination of duplicates, 2 additional

[1] [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1453384548330&uri=CELEX:52015PC0595

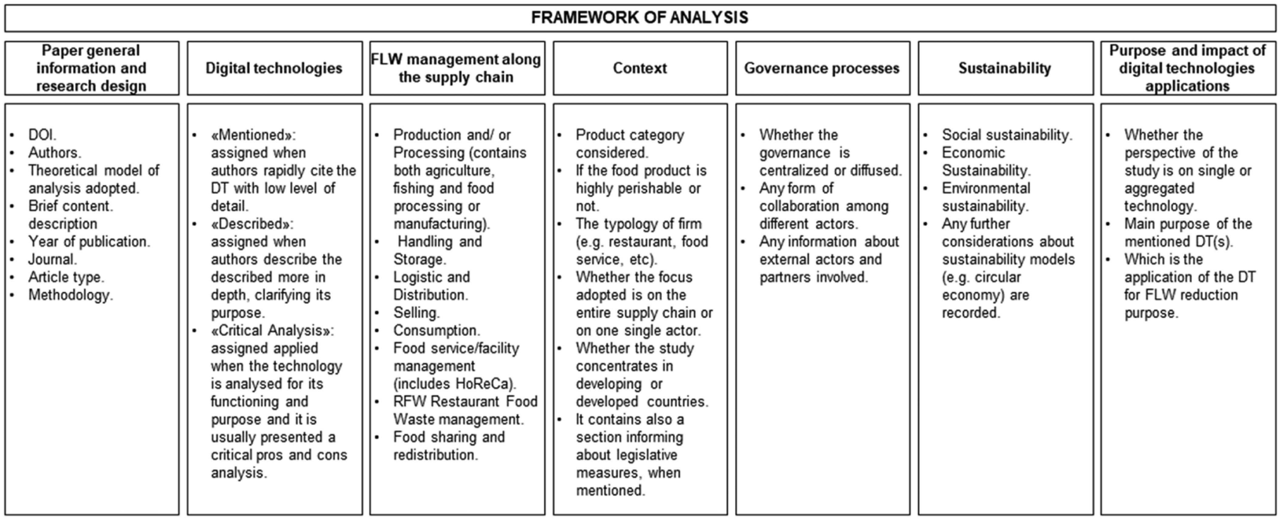

Fig. 2. Framework developed for the analysis of the literature. Source: The authors.

publications that were not immediately retrieved with keywords search were included, resulting in a total of 64 articles.

The same search was conducted by the authors individually, reaching a high inter-rater reliability since the number of results retrieved was the same. Since the retrieved literature was not excessively broad and the topic gained growing attention only in the last few years, we included peer-reviewed management journal articles, books in English, and conference proceedings. Due to the exploratory nature of the review and the limited number of articles, this allowed us to develop a critical analysis of the topic rather than just a bibliometric and quantitative analysis.

We then read each retrieved article in order to ensure that publications addressed the scope of the review. After a close reading of each article, 16 articles were excluded either because digital technologies were not clearly mentioned or because their impact on FLW was not made explicit. The final sample of 48 articles is summarized in the Appendix, while each article is analyzed in Section IV.

Among the papers selected, only six papers use an SLR or literature review approach. Further, the positioning of these papers differs from ours for the following reasons. Benyam et al. [22] systematically review articles on digital technologies specific to agriculture, focusing mainly on the upstream stages of food production (i.e., farming and agriculture). Fernandez et al. [70] perform a bibliographic review concentrating on the postharvest food supply chain, with a particular focus on ecological food packaging, active, and/or intelligent packaging. Kayikci et al. [71] combine an SLR with semistructured interviews in order to investigate blockchain technology implementation in the food supply chain, in which FLW reduction is one of the many different benefits reviewed. Onwude et al. [72] analyze the tools for reducing quality loss only for fruit and vegetable during the packaging, storage, and transportation stages of cold chain operations. Although of review of Hassoun et al. [17] provides a comprehensive analysis of the role of digital technologies for achieving the UN sustainable development goals, it is not focused in particular on the FLW issue. Finally, the review by de Almeida Oroski and da Silva [73] concentrates only on digital platforms for preventing and/or reducing FLW. Therefore, with this SLR, we aim to build on these prior publications by including the literature on the entire supply chain stages, with a particular focus on the effects of digital technologies on FLW prevention and reduction.

IV. Results

The developed framework, presented inFig. 2, classifies the collected papers according to the following seven macro categories.

1) Section IV-A contains general information collected for each article.
2) Section IV-B reports whether the authors mention, describe, or critically analyze each digital technology [29], [74].
3) Section IV-C summarizes the portion of the supply chain in which the mentioned technologies were adopted for addressing FLW.
4) Section IV-D contains information collected about the contextual characteristics, such as the product category considered, the country of analysis, or the firm's typology (e.g., restaurant, food producer, etc.).
5) Section IV-E reports information about the governance processes [62], [75].
6) Section IV-F records which sustainability dimension is addressed in each study, marking if the study considered deals with one or more of the three sustainability dimensions [41], [49].
7) Section IV-G analyzes the scope of the mentioned technologies, focusing on understanding how the technologies address FLW.

First of all, we lay the basis for our literature review by providing a bibliometric understanding of each section of the

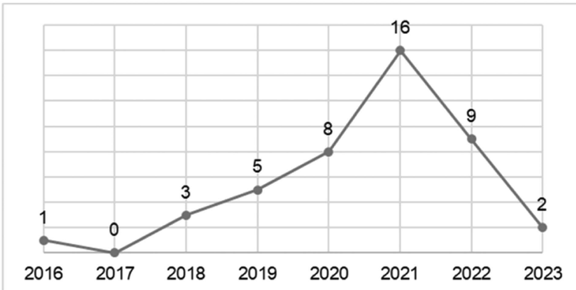

Fig. 3. Distribution of the publication years of the final sample of papers.

TABLE I
THEORETICAL FRAMEWORKS ADOPTED IN THE LITERATURE

Theoretical framework	References
System framework based on four pillars (Environment, Economy, Social considerations, and Governance)	[22]
Availability–Surplus-Recoverability–Waste framework	[77]
Food Waste Hierarchy	[41]
People, Process, and Technology model	[71]
Platform–based sustainable business models	[78]
Theory of Change	[61]
Customer Development framework, Social Enterprise Business Model Canvas.	[79]
Resource-Based View	[47]
PESTEL model	[80]

framework. Each variable of the framework and the emerging research gaps are then analyzed in Section V.

A. Paper's General Information and Research Design

This section provides an overview of the general information collected about the retrieved papers. First of all, the literature on the use of digital technologies for FLW prevention and/or reduction along the AFSC has grown in recent years. The following chart illustrates the distribution of the reviewed papers, thus demonstrating the growing relevance of the topic (see Fig. 3).

As overviewed in Table I, only eight papers adopt a clear theoretical framing and, among them, only one paper adopts an established theoretical lens in operations and supply chain management literature—the resource-based view (RBV) [47]. Other papers frame their research using managerial frameworks [41] specific to FLW management and sustainability literature [22]. For instance, Michelini et al. [61] adopt the theory of change (ToC) framework, which is a methodology for understanding how, why, and when social change happens in a certain context [76].

By grouping the retrieved articles according to each journal's field of study, the cross-disciplinary nature of the topic emerges: the majority of journals deal with sustainability and ecology, which are topics relevant to multiple branches of knowledge, including operations and supply chain management and the agri-food sector (e.g., *Journal of Cleaner Production, Sustainability, Sustainable Production and Consumption, Ecological Economics,* and *Resource, Conservation and Recycling*) while others, especially the conference proceedings, deal with ICT and digital technologies. Other journals deal with the topics of industrial engineering, economics, innovation, and entrepreneurship (see Table II).

TABLE II
JOURNALS LIST

Journal / Conference	Number	References
Resources, Conservation and Recycling	6	[41], [81], [82], [83], [84], [85]
British Food Journal	4	[10], [61], [86], [87]
Sustainability	3	[47], [88], [89]
Waste Management	3	[90], [91], [92]
Industrial Marketing Management	2	[27], [93]
Processes	2	[70], [72]
International Conference on artificial intelligence and Signal Processing, AISP	1	[94]
Journal of Cleaner production	1	[22]
IFIP Advances in Information and Communication Technology	1	[95]
International Journal of Production Economics	1	[96]
IEEE 2nd International Smart Cities Conference: Improving the Citizens Quality of Life, ISC2	1	[77]
Technological Forecasting and Social Change	1	[97]
IEEE Access	1	[8]
Journal of Retailing and Consumer Services	1	[98]
Journal of sensors	1	[99]
Sustainable Production and Consumption	1	[100]
Computers in Industry	1	[101]
Production Planning and Control	1	[71]
International Journal of Entrepreneurship and Innovation Management	1	[80]
Journal of Business Research	1	[102]
Ecological Economics	1	[11]
Journal of Physics: Conference Series	1	[79]
Proceedings of the Annual Hawaii International Conference on System Sciences	1	[103]
Socio-Economic Planning Sciences	1	[104]
E3S Web of Conferences	1	[105]
Journal of Environmental Management	1	[80]
Computers and Electronics in Agriculture	1	[106]
Journal of Food Engineering	1	[107]
2018 IEEE international conference on communications workshops	1	[108]
Procedia Computer Science: 3rd International Conference on Industry 4.0 and Smart Manufacturing	1	[109]
Managerial and Decision Economics	1	[110]
Food Research Internationals	1	[17]
Environment, Development and Sustainability	1	[111]
Waste Management and Research	1	[73]

Table III presents the research methodologies adopted. The most diffused methodology is case studies research, with both single and multiple case studies, followed by interviews. Single case study articles tend to provide detailed descriptive data about FLW [90], while the multiple case studies methodology is used for theory building [87]. Interviews are typically conducted by the authors with managers and directors to understand the relationships among FLW management and the use of digital solutions [87], [27]. Semistructured interviews were used to compare similarities and differences across cases or as a primary method of data collection in a qualitative study [41], [71].

TABLE III
RESEARCH METHODOLOGIES ADOPTED IN THE ANALYZED LITERATURE

Methodology	Number	References
Case studies (Single case study)	7	[10], [88], [90], [91], [92], [93], [108]
		[11], [27], [47], [61], [77], [78], [87], [97]
Case studies (Multiple case studies)	8	[27], [41], [47], [71], [79], [86], [87], [92], [103] [98], [100]
Interviews (Semi-structured interviews)	9	[10], [88], [90], [91], [92], [93], [108] [11], [27], [47], [61], [77], [78], [87], [97]
Interviews (Ethnographic interviews)	2	[27], [41], [47], [71], [79], [86], [87], [92], [103]
Simulation and statistical method	9	[80], [81], [82], [83], [84], [85], [86], [96], [107], [109], [111]
Literature review/Systematic Literature Review (SLR)	6	[17], [22], [70], [71], [72], [73]
Survey	5	[10], [79], [86], [102], [104]
On-field quantitative data collection	2	[83], [99]
Focus Group	1	[61]

Ethnographic interviews are chosen to study user behavior in a certain environment and to grasp the differences between the intended and actual use of the services [98], [100].

The adoption of these varied methods underlines that the research on this topic is still qualitative and exploratory, with the aim of capturing knowledge from practice [112]. Both literature review and SLR were also used, as described in Section III-A. Simulation and statistical methods are employed to develop an in-depth understanding of the relationships among variables, such as the effects of dynamic shelf life and discounting on profit, waste, shortages, and product quality [96]. In other cases, digital twins are adopted for modeling and simulation of fruit's behavior during commercial operations [81], [83], [84], [107]. Surveys are conducted with an exploratory aim, in order to understand consumer out-of-home habits [10], to investigate the key success factors of food sharing platforms [102] or to understand how the pandemic has affected food service processes and operations [104]. On-field data collection is considered as a separate category, as it is adopted to quantitatively study the behavior of certain food products according to the variation of environmental parameters during logistics and transportation [83], or directly collecting data about food waste through sensors [99]. Finally, focus groups are adopted only in one paper [61].

B. Digital Technologies

For each paper retrieved, we review the most relevant digital technology that directly addresses FLW prevention or reduction. As summarized in Table IV, IoT and digital platforms are the most frequently cited technologies. Jagtap et al. [101] present the design of an IoT system for monitoring food and energy waste to support resource efficiency in food manufacturing. This publication serves as a concrete example of improvement in food manufacturing operations and decision making since valuable data generated are analyzed to build KPIs and reports. Digital platforms are typically analyzed more in depth in comparison to IoT. For instance, Schroder et al. [103] provide a classification of food waste platforms that mitigate market inefficiencies promoting sustainable change. Other authors concentrate on a single platform [102], studying the main drivers of the success of food sharing business models.

The other technologies are critically analyzed in the minority of cases. For instance, blockchain technology facilitates the transparency of data collected, thus ensuring the security of food products through cold storage conditions monitoring [8] and throughout the entire food supply chain [71]. Only Vernier et al. [47] critically analyze the adoption of EIS, as they discuss the difficulties to implement ICTs in the agri-food sector and analyze the conditions making EIS a strategic resource.

The topic of data-driven production planning and control to favor sustainability in food supply chain is central in the study by Bresler et al. [95], which is the only paper to directly investigate the value of data in food production planning and control, underlining the need for further analysis. Jagtap et al. [88] illustrate the advantages of image processing in the creation of an automated system for waste tracking. Digital twins are more a niche topic, although they are deeply analyzed in two case studies [69], [71]. Other technologies, such as RFID, AI, intelligent or active packaging, ML, GPS, and RPA, receive less attention. In fact, they are frequently only mentioned, without being analyzed in depth.

C. FLW Management Along the Supply Chain

This section examines which portion of the supply chain has been considered for the application of digital technologies for FLW reduction and/or prevention. We move beyond the traditional supply chain processes—based on the SCOR model: source, make, deliver, and return [114]—to consider the specific food waste management processes throughout the entire life cycle of food products, thus including food service and/or facility management, FW management, and food sharing as a part of the entire agri-food value chain, according to a circular perspective. Incorporating these stages of the supply chain is critical as a large portion of the waste occurs in these stages [10]. The supply chain processes are represented in Fig. 4, which also highlights the level of adoption of digital technologies to achieve FLW prevention and reduction in the reviewed articles. Upstream and downstream processes are classified on the basis of the definition provided by Despoudi et al. [1], which consider all the stages from farming up to preretail as part of the upstream AFSC, while the downstream AFSC includes the stages from retail to postconsumer.

Apart from [41], [80], and [106], which consider the first four steps of Fig. 4 (production and/or processing, handling and

TABLE IV
NUMBER OF "MENTIONED," "DESCRIBED," AND "CRITICALLY ANALYZED" DIGITAL TECHNOLOGIES

Digital technology	Mentioned	Described	Critical Analysis	Total	References
IoT	8	4	7	19	[8], [17], [27], [41], [70], [71], [72], [82], [86], [90], [91], [94], [95], [97], [98], [99], [101], [106], [108]
Digital platforms	3	5	10	18	[10], [11], [22], [77], [78], [79], [87], [93], [98], [100], [102], [103], [104], [105]
Blockchain	7	1	4	12	[8], [17], [22], [27], [47], [71], [72], [104], [80], [86], [89], [110]
RFID	9	1	1	11	[22], [27], [47], [70], [71], [72], [91], [95], [101], [106], [110]
Digital twin	0	3	4	7	[17], [72], [81], [83], [84], [107], [109]
AI	5	2	0	7	[17], [41], [69], [95], [97], [104], [111]
Big data analytics	3	1	2	6	[17], [27], [69], [95], [97], [106]
EIS	3	1	2	6	[22], [27], [47], [95]
Intelligent / Active packaging	4	1	0	5	[22], [41], [72], [113]
Machine learning	4	1	0	5	[41], [82], [97], [99], [109]
Image processing	2	1	1	4	[41], [72], [88], [97]
GPS	2	0	0	2	[27], [56]
RPA (Robotic Process Automation)	2	0	0	2	[17], [27]
Digital twin	0	3	4	7	[17], [72], [81], [83], [84], [107], [109]

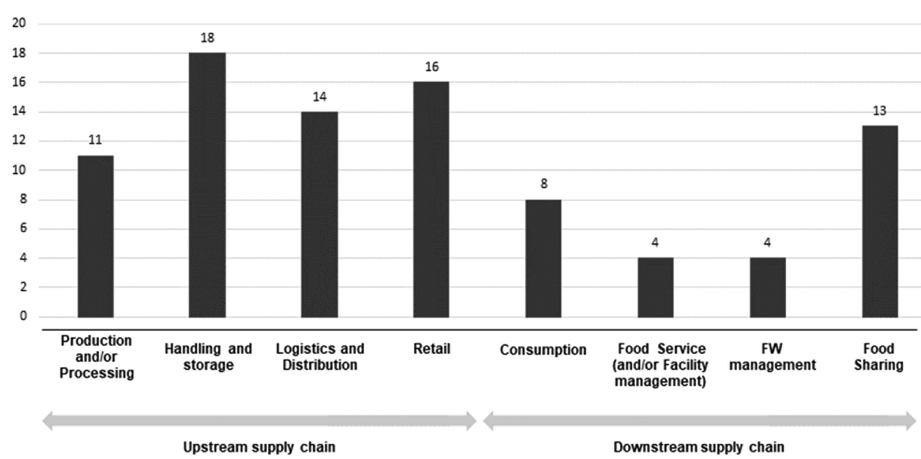

Fig. 4. Number of times in which each stage in the AFSC is at least mentioned.

storage, logistics, and distribution), none of the papers collected consider as unit of analysis the entire supply chain.

The papers aforementioned deal with the supply chain stages almost in a homogeneous way, with a particular focus on the handling and storage stage, while only a few mention the FW management stage [80], [91], [99], [111], and food service and/or facility management. This finding indicates that less effort is directed toward the food waste generated by restaurants, catering, and food service, even though they have a vital role to play in reducing or preventing FLW [115]. In addition, we were expecting higher attention toward the adoption of digital technologies for food loss prevention and reduction at the production stage since production system performances are object of continuous improvement and high efficiency [59]. In Section V, we analyze in detail how each specific technology is related to each stage.

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D. *Context*

The examined papers rarely reveal information about the context of analysis. Specifically, details about the firm's general characteristics are not always provided, and firm size is almost never specified. The adoption of digital technologies is generally discussed without providing a contextual understanding. In other words, it is difficult to comprehend how these technologies should be adapted according to a specific context, while it would be relevant to understand behind the "one-size fits all" approach. Given the scarcity of theoretical perspective, we hope future research will incorporate a contextual perspective.

Regarding the typology of food products studied, many of the papers do not focus on single product category but consider "Food" in general and food surplus of any kind. Other studies focus on a specific product category, such as shellfish [8] or potato [88] for the sake of simplicity, especially when a single technology is tested on field and analyzed in depth.

Most of the papers focus on developed countries. Only Kör et al. [86] provide an overview on the role of context and culture on FLW generation and management by exploring the differences between developing and developed countries.

Finally, considerations about the existence of a legislative framework incentivizing FLW reduction through digital tools are scarce. Benyam et al. [22] report that legislative frameworks are inadequate and governments face various challenges on the regulation and administration of digital technologies for agriculture.

E. *Governance Processes*

Governance is defined as the structure of practices, initiatives, and processes, existing within a given organization and along the supply chain, that ensures that decisions are taken coherently to obtain a long-term, sustainable value [116]. When dealing with sustainability, governance mechanisms from a supply chain perspective are defined as "as practices, initiatives, and processes used by the focal firm to manage relationships with 1) internal functions and departments and 2) their supply chain members and stakeholders with the aim of successfully implementing their corporate sustainability approach" [116, p. 1921].

Only recent publications provide interesting considerations about the changes in governance mechanisms occurring after the introduction of digital technologies targeting FLW reduction. Villalobos et al. [106] state that information-enabled supply chain in which actors have access to real-time data from sensors represents a great opportunity for more efficient use of resources, leading to less waste: however, there can be unintended consequences in terms of power unbalances among actors unable to exploit these technological resources because of lack of capital and/or prepared labor force. In the retrieved papers, the most frequently mentioned aspect regarding governance is collaboration among different actors in the supply chain in order to ensure information sharing.

Digitalization and collaboration among actors within the firm and along the food supply chain are two strongly interrelated topics. Indeed, digitalization requires coordination between actors in order to be effective and, through coordination between supply chain actors, better sustainability performance can be achieved [117]. However, the lack of trust can represent a relevant obstacle to information and resource sharing, with negative consequences for FLW prevention and reduction [118]. FLW prevention can be enhanced through vertical collaborations among supply chain actors and technology providers, which are necessary conditions to exploit the full potential of cutting-hedge technologies [41]. Collaboration is also a critical aspect for building and maintaining a functioning digital platform ecosystem. Moreover, in order to obtain a sustainable change, a closer collaboration among the demand and supply side is required [103].

F. *Sustainability*

This section investigates whether the studies deal with environmental, economic, and/or social sustainability to understand whether the FLW mitigation goal is aligned with sustainability goals. Only nine papers deal with all three dimensions of sustainability, thus underlining the necessity for a more integrated approach towards sustainability. As illustrated in Fig. 5, environmental sustainability is mentioned more frequently than the other two sustainability dimensions.

The literature also highlights the effects on sustainability obtained by preventing and reducing FLW. According to Jagtap et al. [101], by monitoring food and energy waste through IoT at the machine level, it is possible to identify the less efficient processes, thus improving costs and use of resources, as well as supporting decision making in food management. Bresler et al. [95] identify a set of qualitative principles for sustainable data-driven production planning and control; however, it is not clearly defined which data would be useful to integrate those principles, which is currently available, which is not captured, and, ultimately, how to capture and share those data. Fernandez et al. [70] address the sustainability dimension through packaging and logistics efficiency, which in turn helps preventing waste and extends product life in the entire supply chain, according to circular economy principles. Moving upstream in the supply chain, Benyam et al. [22] record the different purpose of digital agriculture technologies and their potential contribution in each sustainability dimension for FLW prevention and/or reduction.

Other studies articulate and classify the business model of digital platforms that create value along social, economic, and environmental sustainability dimensions within AFSC [103]. Food sharing enabled by digital platforms is frequently seen as a quick response of customers to environmental sustainability and social issues [102]. The impact of food sharing platforms has been assessed by Michelini et al. [61], who developed a theoretical framework that captures the activities, outputs, and outcomes of food sharing platforms, linking them to a proposed set of indicators. Platforms for selling restaurants' surplus food offer economic benefits to customers because the meals are sold at a discounted price while also having a positive impact on the environmental sustainability dimension. Indeed, natural resources are used more efficiently and less waste ends up in landfills, with a consequent reduction in carbon dioxide and other harmful emissions [78]. For business models different than food sharing, such as online food provisioning, sustainability is

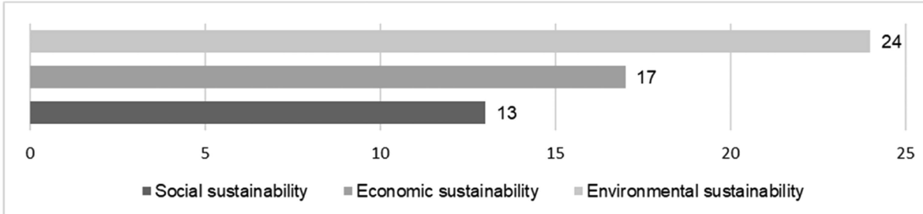

Fig. 5. Number of mentions for each TBL element in the analyzed literature.

not a primary source of value. Indeed, economic convenience and the reduction of the mental load of organizing proper meals are the customers' primary motivations for accessing the service, rather than reducing food waste or reducing meat consumption for sustainability reasons [100].

Finally, only a few studies adopt a circular economy perspective to promote practices for FLW reduction, by simply assuming that wasting food goes against circular economy principles [97] and that technological solutions are essential to translate circular economy principles into specific actions [41].

However, the real impact of FLW prevention and reduction through digital technologies on the aforementioned sustainability dimensions and indicators is rarely measured in a quantitative way. Only Jagtap et al. [101] monitor energy and water consumption jointly with food waste generation. The most significant example of FLW reduction tracking is reported in [90], who adopts an IoT-based FW monitoring system to precisely measure waste, reasons of waste, and related CO_2 emissions and costs at production level. The adoption of such monitoring system results in a reduction of FW and has a positive environmental and financial impact for the organization. In most cases, it is barely mentioned that reducing FLW helps improve environmental sustainability performances, and especially in which measure [81].

G. Purpose and Impact of Digital Technologies Applications

This section reviews the main purpose of the digital technologies explored in the papers, and, in a logical chain, how each purpose is translated into a specific impact on FLW reduction and prevention. The second column of Table V reports the purpose of the implementation of each technology and the third column reports how each technology leads to FLW reduction and/or prevention. Here, the technologies are ordered according to their occurrence emerging from the coding of the literature analyzed. Specifically, the first action in the list (starred) represents the most frequently mentioned result enabled by each digital technology. See Table VI for the definition of each digital technology mentioned.

Concerning the purpose of the digital technologies, it emerges that, overall, the most frequent purposes of digital technologies for FLW reduction and/or prevention are monitoring and measuring, followed by food sharing. Digital technologies can be adopted for monitoring food and ambient conditions, for instance, to provide farmers with data about temperature, moisture conditions, or other parameters [94]; to measure and categories types of FLW [88], [104]; or for sharing food to reduce the likelihood that it ends up in a landfill [102].

In order to answer the research question RQ2, we analyze in depth how each digital technology contributes to reducing and/or preventing FLW, according to the analyzed literature.

Active/Intelligent packaging is mentioned only in Fernandez et al. [70]. Intelligent packaging relies on product data that are collected and registered through barcodes or RFID tags, which allows for product traceability, better inventory management, and better planning and coordination among supply chain actors. Active packaging instead can react to different simulations generated by food or the environment in order to preserve food from quality deterioration. These technologies increase food quality preservation during the handling and storage, logistics and distribution, and retail stages, generating a positive impact on food waste prevention. However, they are characterized by high costs and low consumer acceptance.

AI is especially adopted for performance optimization. For instance, Ciccullo et al. [41] use AI to improve forecasting of both offer and demand for fruits and vegetables. Similarly, Strotmann et al. [104] cluster forecasting tools as mostly intelligent software for data analysis in order to optimize the handling of food. Solutions relying on AI are adopted in food service facilities to track and monitor food waste and, in turn, identify waste reduction opportunities [69]. In the supply chain, AI has great potential to be adopted by actors in the production stage, handling and storage stage, and the retail stage for performance optimization or, through machine vision and image recognition, to predict products deterioration stage or detect reasons for food waste generation [104]. Supermarkets can deploy AI also at the retail level and, when combined with machine learning, it can analyze product data to predict fruits and vegetables remaining time before a transformation to the next deterioration stage. Consequently, AI can improve the supermarkets pricing policies, encouraging customers to choose products that are not at the perfect maturation stage, thus reducing waste disposal and the associated disposal costs [97].

In a digitized supply chain, data come from a variety of different sources (IoT, sensors, etc.); therefore, *BDA* is an essential capability for exploiting the potential of data. The main stages involved in this process for FLW reduction and/or prevention are production, followed by handling and storage, and retail; however, the whole supply chain can benefit from it. Benefits for FLW derive from performance optimization and reduced overproduction: the usage of big data helps reduce defective products by avoiding weak points in the production process, therefore reducing scraps and product damage [27]. BDA can also be used to study consumer's behavior and sales history, especially in the case of promotional plans and seasonal demand

TABLE V
PURPOSE AND IMPACT OF DIGITAL TECHNOLOGIES APPLICATIONS

Digital Technology	Purpose	Impact on FLW reduction and/or prevention
Active / Intelligent packaging	Monitoring. Improve transparency and safety. Improve production planning. Improve coordination.	Food quality preservation*
Artificial Intelligence	Improve forecasting. Monitoring. Tracking.	Performance optimization* Detect reasons for waste Predict deterioration stage
Big data analytics	Improve production planning and control. Improve accuracy in planning and forecasting. Improve Inventory management. Real time data management. Data sharing. Dynamic shelf life. Reduction of defective products.	Performance optimization* Reduced overproduction Production ramp-up or halting Adjusted selling time and price Shelf life increasing
Blockchain	Tracking and traceability. Monitoring. Advanced product transportation and inventory management Real-time order placement Automation of production tasks	Improve transparency and safety* Food quality preservation, reduced contamination risk Identify and predict quality losses Inform customers Prevent FLW
Digital platforms	Sell unsold food. Food sharing. Bypass intermediaries. Allow access to products before deterioration. Increase quantities of food collected and redistributed. Enable last-minute discounts. Online food provisioning. Education. FW data sharing.	Food surplus redistribution* Better meal planning Education Reducing unsold food Inform customers about discounts Improve FW management Ensure FW management transparency
Digital twin	Monitoring. Evaluate different scenarios.	Food quality preservation* Shelf life increasing Identify and predict where quality losses happen Improve cooling during shipment
Enterprise information systems	Performance optimization. Operations efficiency. Information sharing.	Performance optimization* Efficient resource use Improve coordination and communication.
GPS	Food quality preservation Detect causes for waste	Logistics and distribution optimization*
Image processing	Detect quality characteristics. Monitoring. Measuring	Food quality preservation* Detect causes of waste
Machine learning	Improve offer and demand forecasting. Enhance advertising on social media	Performance optimization* Education
RFID	Monitoring. Route optimization.	Food quality preservation* Ensure FW management transparency
Robotic Process Automation	Enable automated sorting process. Reduction of human intervention.	Errors reduction* Sorting time reduction

The table lists the scope of implementation of each digital technology and the actions that each technology performs on FLW. Refer toTable III for specific references. The starred (*) sentence represents the most frequently mentioned action of each technology on FLW prevention and reduction.

[95]. In turn, this helps improve accuracy in planning and forecasting, already described as the typical area of improvement supported by BDA [119], and reduces overproduction. BDA, through AI and machine learning enable dynamic pricing, storage, and item display, all of which reduce retailer's food losses [97].

Blockchain is likely to be adopted during the handling and storage stage, as well as the logistics and distribution stages, for improving transparency and traceability of information exchange, thus ensuring food safety throughout the entire supply chain [120]. Blockchain-based multisensor monitoring systems are used for capturing changes in shellfish storage conditions and prevent quality losses, simultaneously ensuring data security and reliability [8]. Kayikci et al. [71] propose the use of blockchain technology to promote food journey traceability: by relying on smart contracts between supply chain members, it is easier to trace products back to the origin in the case of food contamination, thus detecting the illness source and ensuring that other food is discarded if it was in contact with contaminated ingredients. Information collected can also be made accessible at the customer level so that customers can trace the origin of purchased products. Regusto platform, one of the digital tools cited by Strotmann et al. [104], relies on blockchain technology to track transactions of donated products, ensuring greater transparency and easier data management. However, the effects of blockchain technology on FLW reduction or prevention seem often indirectly linked to the primary goal of better product transparency and traceability. Only Yontar et al. [80] individuate

TABLE VI
DEFINITIONS OF THE TECHNOLOGIES AND TOOLS REFERRED TO AS "DIGITAL TECHNOLOGIES" IN THE TEXT

Digital Technology	Definition	Reference
Artificial intelligence	"AI is a field in computer science encompassing the development of systems capable of performing tasks that normally necessitate human intelligence".	[136]
Big data analytics	"Big data analytics implies two perspectives: big data (BD) and business analytics (BA). BD refers to high-volume, high-velocity, and high-variety sets of dynamic data that exceed the processing capabilities of traditional data management approaches. BA is the study of the skills, technologies, and practices used to evaluate organization-wide strategies and operations continuously to obtain insights and guide the business planning of an organization."	[137]
Blockchain	"Blockchain is a distributed database, which is shared and agreed upon a peer-to-peer network. It consists of a linked sequence of blocks, holding time stamped transactions that are secured by public-key cryptography and verified by the network community. Once an element is appended to the blockchain, it cannot be altered, turning a blockchain into an immutable record of past activity."	[138]
Digital platforms	"Digital platforms, in particular in this case Transaction Platforms are defined as "A technology, product or service that acts as a conduit (or intermediary) facilitating exchange or transactions between different users, buyers, or suppliers."	[140]
Digital twin	"A digital twin is a virtual model and comprehensive depiction of the system used to understand the performance parameters, ameliorate processes, and effectively enhance value-added activities. A digital twin is a digital counterpart of the physical systems based on a simulation that deals with design systems and optimizes them for improved efficiency."	[141]
Enterprise Information Systems	"Enterprise Information Systems (EIS) can be defined as systems for business management, encompassing modules supporting organizational functional areas such as planning, manufacturing, sales, marketing, distribution, accounting, financial, human resources management, project management, inventory management, service and maintenance, transportation and e-business."	[142]
GPS	"Satellite-based navigation systems are one of the most indispensable technologies in the present-day world that have made a vast improvement since the day of its inception due to global availability of signal and performance. It allows measuring positions in real time with an accuracy of up to a few centimeters on the Earth."	[143] [143]
Image processing	"Image processing is defined as the use of computerized algorithms for the analysis of images with respect to an application."	[145]
Intelligent/active packaging	"Intelligent packaging is defined as "a control system inside packaging which is able to perform intelligent functions such as standby, detection, tracking, recording, and communicating in order to provide individual links in the packaging chain". Active packaging instead "reacts to different stimulations from food or the environment to allow monitoring or maintaining food quality and safety in real time."	[70]
Internet of Things	"IoT is a conceptual framework that leverages on the availability of heterogeneous devices and interconnection solutions, as well as augmented physical objects providing a shared information base on global scale, to support the design of applications involving at the same virtual level both people and representations of objects."	[144]
Machine learning	"Machine learning (ML) is a subset of artificial intelligence that develops dynamic algorithms capable of data-driven decisions, in contrast to models that follow static programming instructions. ML is concerned with enabling computer programs automatically to improve their performance at some tasks through experience."	[146]
RFID	"RFID is an electromagnetic proximity identification and data transaction system. Using ''RFID tags'' on objects or assets, and ''readers'' to gather the tag information, RFID represents an improvement over barcodes in terms of non-optical proximity communication, information density, and two-way communication ability. Operational RFID systems involve tags and readers interacting with objects (assets) and database systems to provide an information and/ or operational function."	[151]

blockchain technology as the first critical success factor for a sustainable supply chain by preventing FLW at many stages of the supply chain, for instance, through advanced product transportation and inventory management and facilitating real-time order placement and automation of production tasks through smart contracts.

Digital platforms are often analyzed in-depth, suggesting that these platforms are attracting the attention of scholars. However, most of the solutions are concentrated on food sharing, which addresses food waste through food surplus redistribution [87], [93]. Some solutions focus on the consumption stage, with the aim of promoting better meal planning through online food provisioning and educating consumers on food waste [100], [103]. Only two papers mention the possibility of creating platforms for connecting actors more upstream in the supply chain, such as allowing farmers to bypass intermediaries and connect directly to restaurants, retailers, and consumers, thus mitigating potential food losses occurring postharvest [22]. These platform initiatives are classified as "Alternationists," who effectively shorten the supply chain by cutting out middlemen and thus also cutting food waste [103].

Digital twin is adopted exclusively for monitoring food products. For instance, Defraeye et al. [81] use digital twin to simulate the thermal behavior of mango fruits throughout the cold supply chain. Digital twin can reduce FLW during transportation by identifying where quality losses occur and, as a result, improve cooling during shipment, reducing product damage and quality losses. Preserving food quality during shipment leads to an increased shelf life [72]; moreover, digital twin can provide a picture of the products' conditions in the inventories, thus prioritizing the shipment of fruits in a more advanced maturation stage [109]. Similar considerations are made by Shoji et al. [83], [107], analyzing real-time transportation, handling, storage, and shelf data of different fruits and vegetables.

Enterprise information systems, such as ERP, WMS, or PLM, are frequently mentioned, but only in two cases, they are critically analyzed. In the first case, Vernier et al. [47] state that these tools will enable "more efficient activity with fewer resources and fewer losses in the logistic sector." In general, these tools are described as enablers of performance optimization, communication, and information sharing between supply chain actors, with the aim of improving coordination and performance [47]. Sharing real-time data through systems improves production planning and control, due to the greater alignment of supply and demand, which promotes accurate inventory levels and in turn increasing the remaining shelf life of products downstream in the supply chain [95]. Only Annosi et al. [27] mention in detail the system adopted by the actors involved in the research (e.g., ERP, WMS, CRM) but does so without describing the direct effect on FLW prevention and reduction. As a result, we have only poor, generic information about how EIS tools actively contribute to FLW reduction.

GPS is mainly employed in logistics and distribution, enabling route optimization [22] and route tracking, thus promoting food quality preservation. It also ensures transparency in FW management activities and avoids illicit activities [91].

Image Processing is adopted to generate a table of the rejected food products and of the reasons behind waste generation, also detecting waste causes [88]. Onwude et al. [72] apply image processing technology to monitor food quality losses of fruits and vegetables during transportation. In other cases, sensors and cameras are adopted to detect food deterioration stage for managing dynamic pricing, storage, and item display in supermarkets [97].

IoT is one of the most cited technologies in the analyzed literature. It is diffused throughout the entire supply chain to achieve a wide variety of objectives. Indeed, the IoT can be extended to the entire supply chain in order to measure and disseminate information, facilitate control, planning, and optimization, as well as promoting forecast accuracy of quantities to be planted by farmers, improving the use of natural resources [97]. Those improvements affect downstream supply chain stages, in which reducing farmer's costs allows supermarkets to offer lower prices. It can be harder to establish a direct purpose of IoT, since in most cases, it is adopted in combination with other technologies, such as RFID or blockchain. However, we can establish that, in general, IoT technology is employed with the aim of monitoring and detecting food deterioration stage and quality losses in real time, measuring and categorizing FLW.

Companies use IoT solutions to track and monitor shipments, especially of refrigerated products [27], in particular, fruits and vegetables [72]. Banerjee et al. [94] propose IoT as a tool for farmers working in remote areas, as it improves food storage conditions by constantly monitoring warehouse parameters leading to reduced food loss and increased food safety. When combined with image processing, BDA, and machine learning, loT provides the data for enabling AI-based dynamic pricing by collecting data about the deterioration stage of fruit and vegetables [97], with positive consequences for food waste reduction [96]. IoT sensors (such as weight sensors or gas detectors) are also employed for analyzing the typology of food wasted and facilitating decision making during production. For instance, Jagtap and Rahimifard [90] analyze the case of a ready meal factory, where IoT sensors are employed to obtain detailed breakdown of the products wasted by identifying the type of waste, the reasons for its generation, and the real-time monitoring of the wasted amount. Similarly, IoT is used to monitor and optimize food waste generation and energy and water consumption in food manufacturing and in turn increase operations efficiency [101]. A similar study was conducted by the same authors on the potato packing process to identify why potatoes are rejected and optimize the process [88]. Digital technology in combination with IoT sensors was also used to monitor and track the entire restaurant food waste (RFW) collection–transportation–disposal process. In this case, IoT guaranteed better law enforcement in response to RFW malpractice and optimized RFW management [91].

Machine Learning algorithms enable performance optimization through improved offer and demand forecasting, therefore reducing the production of surplus food [41]. The use of machine learning is also documented at the consumer level [82], in which algorithms measured and improved the reach of social media advertisements related to household waste management, thus increasing customers' awareness about the FW issue.

RFID is often used during logistics and distribution, and handling and storage. RFID tags can be used to design optimal distribution routes for food refrigeration trucks, thereby reducing spoilage [22], or to track the transportation of RFW [91]. RFID can collect and transmit data in real-time to provide a picture of the supply chain's performance from production to inventory [95]. RFID has also been applied as a tool in product packaging for identifying internal and external changes in product status [22] and to acquire information about the RFW generation [91].

Finally, *Robotic Process Automation* is adopted, especially during handling and storage, and production process to improve errors reduction [27] and reducing sorting time [41]. However, RPA is rarely mentioned with respect to the previous technologies.

V. Discussion

Building on the results presented in Section IV, we provide a critical discussion by analyzing patterns and relationships existing between the frameworks' building blocks (see Fig. 2). The findings and the research agenda are represented in the framework in Fig. 6. First of all, the central part of the framework shows the contribution of each technology to FLW reduction and/or prevention in each supply chain stage, as described in Section IV-G. The lower part of the framework underlines the research gaps, which in turn give space for a research agenda.

As described in Section IV-A, a limited number of papers are build on existing theoretical frameworks. Moreover, given the prevalence of exploratory research methods such as case studies

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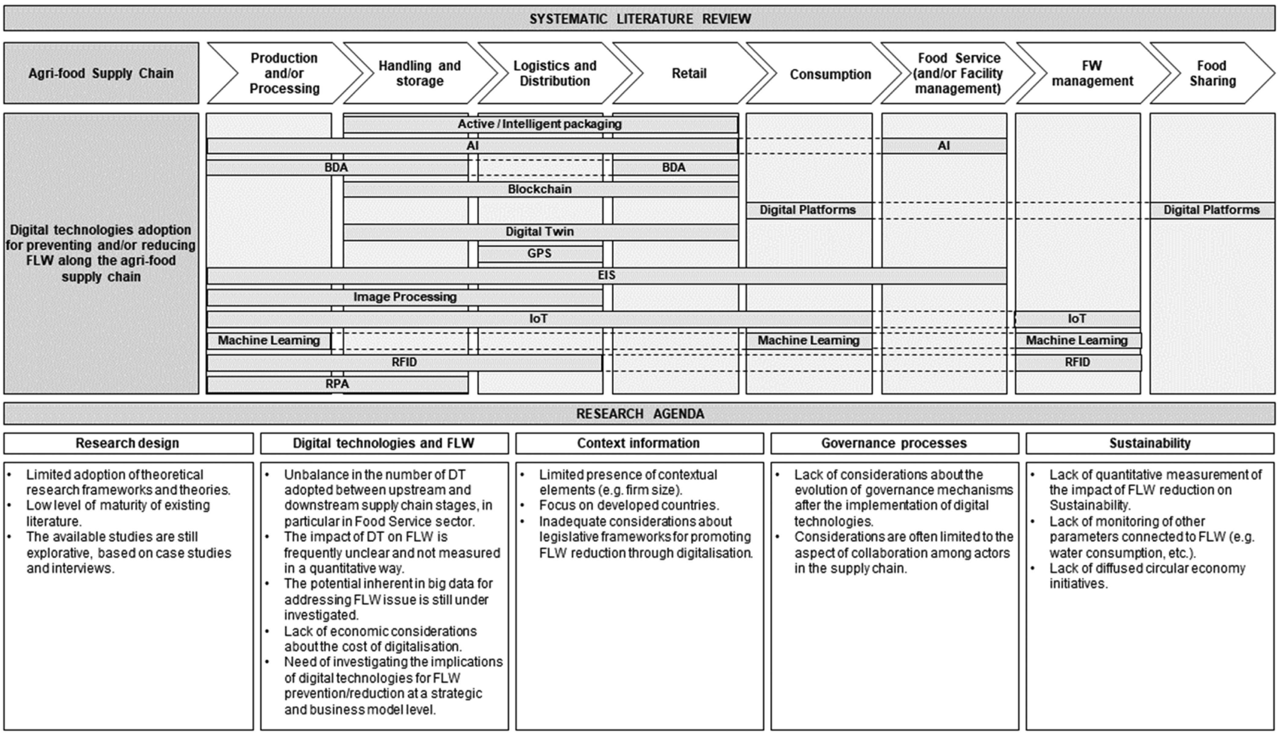

Fig. 6. Discussion framework. The horizontal bars refer to the presence of a certain technology at a determined supply chain stage. When the technology is not adopted in a certain stage but it is adopted in the nearby stages; we use the dotted lines. Source: The authors.

or interviews, and the scarce use of theoretical frameworks and models, the literature is in the early stages of maturity [121].

Therefore, after discussing the state of the art of the literature, we expect it to move forward to theory building and start answering "how" and "why" questions [112].

It emerges that digital technologies are more frequently adopted in the earlier stages of the supply chain (i.e., production and processing, handling and storage, and logistics and distribution). Digital platforms, mobile, and web applications are the most diffused technologies in the downstream part of the AFSC [10], [97], [122], while solutions such as BDA, blockchain, digital twin, IoT, and image processing are more frequently adopted upstream in the supply chain [16], [21], [72]. In order to clarify the drivers that motivate different actors to adopt digital technologies throughout the supply chain, we summarized the identified gap in the following questions*: are upstream AFSC actors more interested in efficiency resulting from food loss and waste reduction and prevention through digital technologies? On the other hand, are downstream AFSC actors more connected to the final consumer and, in turn, more focused on environmental and sustainability implications related to digital technologies adoption?*

From our analysis, the perception emerges that while digital transformation helps create valuable insights from the collected data, it seems that companies in the agri-food context are still not exploiting the full potential of this data: data sharing and integration among supply chain actors is still limited, thus reducing the added-value that could be made available for the entire AFSC [123], including positive effects on economic, environmental, and social sustainability [27], [98]. While the debate in the context of data-driven AFSCs is evolving, there is immense, yet under-investigated, potential in big data and digital technologies for directly addressing FLW prevention and reduction, according to a TBL perspective [97]. *To what extent are data generated through the digitalization of AFSC analyzed for FLW prevention and reduction purposes? Are data about FLW collected and analyzed at the single firm level or at a more extended level while considering the entire supply chain and the impact on society, economy, and the environment? Or is FLW obtained as a result of a general operations efficiency improvement between single company boundaries?*

Digital transformation undoubtedly brings positive cost reduction outcomes in companies [125]; however, the literature does not consider the capacity of FLW prevention and reduction measures through digital technologies to lower costs across different AFSC processes. Resulting economic benefits have to be weighed against the high costs of technologies implementation [31]. Moreover, focusing only on economic benefits associated with FLW prevention and reduction would be reductive: once again, it is of primary importance to identify the environmental and societal costs that can be improved by the digitalization of AFSC for FLW prevention and reduction [126], [127]. *What is the tradeoff between financial, social, and environmental sustainability, attributable to FLW prevention and reduction measures through digital technologies, and the costs associated with the implementation of such technologies along the AFSC?*

When considering the business model implications of FLW prevention and/or reduction through digital technologies, it seems that the majority of considerations focus on using digital platforms to redistribute food surplus. Moreover, by connecting different actors, platforms may offer new business opportunities [103], especially in the final stages of the supply chain [102]. In this context, the debate is providing insights on the business model canvas building blocks [128] characterizing digital platforms, such as the revenue streams [93], customer segments and relationships [79], or key success factors [102]. Nevertheless, the same innovative potential is not adequately considered for other digital technologies that could enable new sustainable and data driven business models and sustainable supply chain strategies [35], [129], [130], with the aim of reducing or preventing FLW. For instance, blockchain works as a trust enabler between different parties of multisided platforms [131], introducing changes at the business model level [13], as described in the case of Regusto app [61]. In the same vein, a more strategic understanding is still required as the main analyzed papers focus more on operational side and on specific cases. The literature underlines that sustainability leaders are those companies that are able to translate their sustainability strategy into specific governance mechanisms characterized by a triple bottom line approach throughout the entire supply chain [116]. *What are the strategic implications of data driven technologies in enabling effective supply chain governance and the development of sustainable business models with the purpose of reducing or preventing FLW?*

Context does not play an essential role in any of the analyzed papers, apart from Kör et al. [86], providing an overview on the role of context and culture on FLW generation and management by exploring the differences between developing and developed countries. Therefore, little information is available about, for instance, firm size, even though a firm's size can be one of the variables to take into account when exploring the incentives in investing in innovation for FLW reduction [48]. Only Annosi et al. [27] mention the difficulties of small and medium enterprises face when investing in innovation. Moreover, since the retrieved articles mainly focus on developed countries, it is necessary to investigate the adoption of digital technologies for FLW reduction in developing countries, where the majority of losses occur in the upstream part of the supply chain [52] and other contextual variables may need to be considered (e.g., lack of infrastructure, technological competences, and political context [132]). *How do contextual elements (e.g., firm size, level of a country's economic development, management education) impact willingness to adopt digital technologies for FLW reduction or prevention purpose?*

Policymakers play an important role in setting the right incentives and institutional rules once identified as the main sources of costs. Only when digital technologies and public policies are combined can FLW be reduced and natural resources preserved [97]. Therefore, the institutions become an essential stakeholder to consider in achieving FLW reduction. *What are the right incentives for addressing FLW issue through the digitalization of AFSC and what is the role of policymakers?*

It is also important to consider the impact of digital technologies adoption on the coordination and control mechanisms of the interorganizational relationships and on company governance [75]. These transactions are in turn enabled by the establishment of an adequate governance structure, which has additional costs and challenges [133]. However, apart from widely shared considerations about the necessity of stronger collaboration and information sharing within actors, it is important to answer the following question: *what are the changes required in governance mechanisms due to the introduction of digital technologies in AFSC for FLW prevention and reduction?*

While we were expecting a limited understanding of the governance mechanisms in this review, the lack of quantitative measurement of the impact of FLW reduction on sustainability (social, economic, and environmental) was quite unexpected. Even though digital supply chain applications are known to promote an ecofriendly approach to business and to incentivize firms to accomplish sustainability goals [27], [134], the impact of digital technologies on the environment for FLW reduction is rarely quantitatively measured or analyzed, such as in [8].

Authors are aware that reducing FLW and improving operations efficiency can improve supply chain sustainability [88], [95], [101]. However, this impact is almost never measured with specific indicators, such as reduced CO_2 emissions, donated meals, water and energy consumption, land spoilage, and labor or capital. A more precise quantification of sustainability impacts is also at the basis for the implementation of effective circular practices [63]. Therefore, it is critical to conduct further research that answers the following questions: *how to quantitatively measure the impact of FLW reduction and prevention on the three sustainability dimensions? What are the appropriate indicators to consider in order to monitor and measure this impact? How do digital technologies facilitate the adoption of circular economy principles in AFSC for preventing and reducing FLW?*

VI. Theoretical and Practical Implications and Future Directions

From the present study, it emerges that both scholars and practitioners are increasingly interested in data-driven AFSC and on the goal of preventing and/or reducing FLW through the adoption of digital technologies, in line with UN Sustainable Development Goal on responsible production and consumption (Target 12.3) and European Green Deal guidelines. Therefore, we highlighted the opportunities for advancing both theory and practice in order to make FLW prevention and/or reduction a priority issue to address when adopting new digital tools in agri-food systems

A. Theoretical Implications

From this review it emerges that more focused studies are still required. The main objective of a significant number of contributions was often not directly related to FLW management but rather to AFSC digitalization, limiting the actions of FLW prevention and/or reduction to monitoring and measuring. Building on previous studies, and specifically on the existing literature reviews on the topic, (e.g., [17], [22], [27], [106]), the present work extends the perspective on technology adoption for FLW prevention and/or reduction, first of all by including an integrated vision on the agri-supply chain. Moreover, we provide considerations that go beyond the weighting of potential opportunities and barriers of the adoption of digital technologies for FLW prevention and/or reduction, thus including in our research agenda the need of exploring the context-related issues of such technological applications, the governance changes, and the opportunity to create a positive impact on sustainability from a triple bottom line perspective.

B. Practical Implications

We include managerial recommendations to stimulate practitioners in understanding the value that lies in digital technologies even though the digitalization process often requires additional economic and organization efforts. Digital technologies in agri-food context may serve as an opportunity to promote sustainable practices, a circular economy, innovative business models, and new governance mechanisms. Therefore, in order to support a business able to respond to higher sustainability standards, it seems necessary to concentrate the efforts on FLW prevention and reduction not only to maximize the efficiency at the company level but also to consider environmental, social, and economic implications at the supply chain level. In this way, we hope this literature review will shed light on the relevance of the topic and stimulate managers' in investigating the implications of adopting digital technologies for preventing and/or reducing FLW on the supply chain operations, governance mechanisms, and sustainability goals. Finally, advancing theory on FLW prevention and reduction through digital technologies can help policymakers who seek to promote sustainable practices in agri-food industry. It will allow them to use indicators and data originating from digital technologies for decision making and for creating incentives that encourage more sustainable organizations and supply chains.

VII. Conclusion and Limitations

The present study is an SLR to critically analyze cutting edge research focusing on the adoption of digital technologies for FLW reduction and/or prevention across the entire AFSC. Digital technologies find several applications in each stage of the AFSC, such as by collecting and monitoring agricultural activities through IoT and by analyzing large dataset through AI and machine learning; or supporting managers in decision making with data collected throughout the supply chain, fostering better demand–production coordination decisions [106]. However, only a limited number of publications analyze in depth how each digital technology contribute to the prevention and/or reduction of FLW across the AFSC, despite the recognized impact that wasting food has at a social, economic, and environmental level [27], [52], [135], [127]. Although in recent years we observed a significantly growing attention towards the topic among academics, as well as the increased interest among practitioners in the agri-food system, it emerges that the analyzed body of literature is still at an exploratory level, providing fragmented insights on specific implementation cases and often failing to provide practical guidance to practitioners in implementing digital technologies for FLW prevention and/or reduction.

Summarizing the main results, digital technologies are more frequently adopted in the earlier stages of the supply chain and IoT and digital platforms are the most frequently cited technologies. IoT is diffused throughout the entire supply chain in order to measure and disseminate information, facilitate control, planning, and optimization, as well as promoting forecast accuracy of quantities to be planted by farmers, improving the use of natural resources and reducing waste. When combined with image processing, BDA, and machine learning, loT provides the data for enabling AI-based dynamic pricing by collecting data about the deterioration stage of fruit and vegetables with positive consequences for food waste reduction. Digital platforms are diffused instead in the downstream supply chain for avoiding food waste through food surplus redistribution.

Moreover, none of the papers collected consider as unit of analysis the entire supply chain, thus resulting in only limited considerations about the changes in governance mechanisms occurring after the introduction of digital technologies targeting FLW reduction. Surprisingly, the real impact of FLW prevention and reduction through digital technologies on the aforementioned sustainability dimensions and indicators is rarely measured in a quantitative way. The external context does not play a central role in any of the analyzed papers, apart from Kör et al. [86], which provide an overview on the role of context and culture on FLW generation and management, by exploring the differences between developing and developed countries; thus, it is an important factor to consider in future analysis discussing about the adoption of digital technologies for FLW prevention and/or reduction. Finally, a research agenda is provided to identify future research opportunities and gaps and to provide guidance on the subject area that require further research, as the limited understanding of the evolution of the governance mechanisms occurring across the supply chain after the introduction of digital technologies for preventing and/or reducing FLW, the contextual information, the data management, and the opportunity to create a positive impact on sustainability from a triple bottom line perspective.

This study presents some limitations. In particular, limitations are related to the generalizability of the findings, given that adopting digital technologies exclusively for reducing and/or preventing FLW is a niche topic.

Appendix

In this section, we provide additional explanation on the article selection process and we provide a definitions for each digital technology mentioned in the text.

Search query: TITLE-ABS-KEY ("digital" OR "digitalization" OR "digitalisation" OR "industry 4.0" OR "technolog∗" AND "food waste" OR "food loss" OR "food loss and waste") AND (EXCLUDE (SUBJAREA, "CENG") OR EXCLUDE (SUBJAREA, "BIOC") OR EXCLUDE (SUBJAREA, "CHEM") OR EXCLUDE (SUBJAREA, "MEDI") OR EXCLUDE (SUBJAREA, "MATE") OR EXCLUDE (SUBJAREA, "PHYS") OR EXCLUDE (SUBJAREA, "IMMU") OR EXCLUDE (SUBJAREA, "EART") OR EXCLUDE (SUBJAREA, "MATH") OR EXCLUDE (SUBJAREA, "NURS") OR EXCLUDE (SUBJAREA, "PHAR") OR EXCLUDE (SUBJAREA, "HEAL") OR EXCLUDE (SUBJAREA, "PSYC") OR EXCLUDE (SUBJAREA, "VETE") OR EXCLUDE (SUBJAREA, "ARTS") OR

EXCLUDE (SUBJAREA, "NEUR") OR EXCLUDE (SUBJAREA, "Undefined") OR EXCLUDE (SUBJAREA, "ENER")).

Final sample of papers: [8], [10], [11], [17], [22], [27], [41], [47], [61], [70], [71], [72], [73], [77], [78], [79], [80], [81], [82], [83], [84], [85], [86], [87], [88], [89], [90], [91], [92], [93], [94], [95], [96], [97], [98], [99], [100], [101], [102], [103], [104], [105], [106], [107], [108], [109], [110], [111].

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Caterina Trevisan received the M.Sc. degree in management engineering from the Politecnico di Milano, Milano, Italy, in 2021. She is currently working toward the Ph.D. degree with the University of Trento, Trento, Italy.

Her current research interests include circular economy and digitalization in the context of supply chain management, with a specific focus on the agri-food and manufacturing sectors.

Marco Formentini received the Ph.D. degree in management engineering from the University of Padova, Padova, Italy, in 2012.

He is an Associate Professor with the University of Trento, Trento, Italy. He held appointments with Cass Business School, University of Bath, and Audencia Business School. His research has been published in leading journals, including the *Journal of Product Innovation Management*, *International Journal of Operations and Production Management*, *Industrial Marketing Management*, *Journal of Purchasing and Supply Management*, *European Journal of Operational Research*, *International Journal of Production Economics*, *Journal of Cleaner Production*, and *Journal of Enterprise Information Management*. He is currently an Associate Editor for the *Journal of Purchasing and Supply Management*, and sits in the Editorial Board of the *International Journal of Operations and Production Management*, *Journal of Business Logistics and Cleaner Logistics*, and *Supply Chain*. His research and teaching focus on operations and supply chain management. In particular, his work examines sustainable supply chain management (with a specific interest in agri-food supply chains), strategic sourcing, and digital transformation.