Journal of Industrial Information Integration 45 (2025) 100851

Contents lists available at ScienceDirect

Journal of Industrial Information Integration

journal homepage: www.sciencedirect.com/journal/journal-of-industrial-information-integration

Review article

Digital twin-enabled regional food supply chain: A review and research agenda

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A R T I C L E I N F O

Keywords:
Digital twin
Regional food supply chains
Sustainability
Resilience
Human-centricity

A B S T R A C T

Sustainable, resilient, and efficient Regional Food Supply Chains (RFSCs) are critical to addressing global challenges such as food security, climate change, and resource optimization. Digital Twins (DTs) have emerged as powerful tools for real-time monitoring, predictive analysis, and process optimization, providing actionable insights for the modernization and integration of RFSCs. Our systematic literature review of 133 studies reveals how DTs can transform RFSCs and the challenges and opportunities associated with their adoption. The findings suggest that DTs enhance RFSC management by facilitating informed decision-making, improving resource efficiency, reducing waste, and promoting regional resilience to external disruptions. This work advances the state of the art by identifying the unique role of DTs in optimizing each process within RFSCs, from production to consumption. Key contributions include (1) identifying the potential of DTs to improve sustainability, resilience, and efficiency in RFSCs, (2) analyzing the challenges of DT interoperability, data integration, and cybersecurity, (3) exploring how DTs can foster regional development through improved traceability and logistics, and (4) presenting an annotated research agenda. This review offers a comprehensive theoretical framework and practical guidance for researchers and practitioners leveraging DTs in RFSCs to create sustainable, human-centric, and resilient supply chains at a regional scale.

1. Introduction

Food supply is a major priority in an era marked by health crises such as the COVID-19 pandemic, armed conflicts, and the effects of climate change [1,2]. Complex processes, long transport distances, and dependence on global markets usually characterize large food supply chains. They are particularly vulnerable to disruptions, resulting in significant delays, more waste, and difficulties adapting quickly to shocks. In contrast, Regional Food Supply Chains (RFSCs) are more resilient due to geographical proximity, community integration, and less dependence on logistics networks. However, even these regional chains face challenges, such as the fragmentation of processes and the need for modernization to ensure their competitiveness and sustainability [3,4].

It is imperative to align RFSCs with societal goals. For example, recent events such as COP-29 reinforce the urgency of resilient food systems [5]. On the one hand, the 2030 Agenda [6] emphasizes goals such as eradicating hunger (SDG 2) and promoting sustainable consumption and production patterns (SDG 12). On the other hand, the Paris Agreement [7] stresses the urgency of limiting global warming to 1.5ºC, recognizing the importance of more efficient and sustainable production and distribution systems. In addition, the concept of Industry 5.0 [8], which places sustainability, resilience, and human well-being at the heart of industrial innovations, highlights the need for human-centered technological solutions to support the transformation of supply chains.

Digital Twins (DTs) are one of the most promising solutions for adapting food supply to the requirements of this century. DTs create dynamic digital representations of physical systems, enabling real-time monitoring, advanced simulations, and process optimization [9]. Integrating data from multiple sources provides adaptable and efficient management of food supply chains (FSCs), mitigating vulnerabilities and promoting agile responses to changes in the external environment. In addition, they promote greater transparency and traceability, fundamental elements for building consumer confidence and implementing more sustainable practices [10–12].

This article follows a concept-centric systematic literature review to investigate how DTs can transform RFSCs, highlighting their practical applications and impact. Studies on the role of DTs in RFSCs are still

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https://doi.org/10.1016/j.jii.2025.100851

Available online 12 April 2025

scarce. Therefore, our work aims to bridge this gap by combining knowledge on food supply chains with research that addresses the application of DTs in regional contexts (e.g., smart territories (ST), smart regions, smart cities, and other territorial dimensions). A research agenda is proposed to outline the main challenges and opportunities. The Research Question (RQ) guiding this review is:

- ***RQ:*** *What challenges and opportunities are associated with adopting DTs to integrate RFSCs?*

This study makes theoretical and practical contributions, highlighting how DTs can empower local actors, strengthen regional economies, and promote sustainable practices. For practitioners, this research provides strategies to optimize operations, reduce emissions, and integrate emerging technologies, enhancing sustainability and resilience in RFSCs. For theory, the review establishes a conceptual framework that links DTs to digital transformation and sustainability while proposing a research agenda to address challenges like interoperability and data security.

The remainder of the article is organized as follows: Section 2 presents key topics of the literature review (DTs, FSC, STs). Next, Section 3 describes the systematic and concept-centric review method used to select and analyze the articles. Section 4 details the results obtained from the analysis of the 133 manuscripts. Section 5 discusses the findings, examining the interrelationships between the key concepts studied and suggesting an annotated agenda for future work. Finally, Section 6 summarizes the main conclusions, strengths, and limitations.

2. Background

2.1. Digital twins

The concept of DT emerged in 2002 when Grieves proposed an accurate digital representation of a physical product, highlighting the importance of integrating product lifecycle management [13]. NASA later adapted and expanded this idea to improve the management and maintenance of complex space systems, using digital simulations to predict performance and identify potential problems [14]. Today, the concept has evolved and is widely applied in various industries, from manufacturing [15] to healthcare [16] and infrastructure management [17]. A DT can be a digital replica of anything in the real world, including logistical systems [18], crops [19], or entire environments [20]. We can define a DT as a complete information system (IS) that receives real-time data from a real-world object or system as inputs and produces outputs, such as actions in the environment, predictions, or simulations of how its physical counterpart will be affected [21].

DTs can involve 3D representations [22,23], but are not restricted to a single technology. It can be structured into several interconnected components: (1) digital data model, (2) real-time monitoring and control, (3) data storage, (4) big data analytics and simulation, and (5) data visualization. The digital data model represents the physical and functional state of the replicated entity and is essential for building a solid and accurate database [24]. Real-time monitoring and control allow DTs to respond quickly to changes in the physical environment. This is crucial for maintaining synchronization between the digital and physical models, providing continuously updated data [25]. This data can be collected through sensors and Internet of Things (IoT) devices, as well as human input. The same principles apply to control, which can be autonomous (via actuators and robotics) or require human intervention. Due to the large amount of data generated, more advanced data storage technologies are necessary (e.g., data lakes, data warehouses, data pipelines) [26]. Big data analytics and simulations are used to predict future behavior and optimize processes. Supported by Artificial Intelligence (AI) and Machine Learning (ML), this functionality enables detailed analysis of large datasets, identifying patterns and insights that can be used to improve decision-making [27]. Finally, data visualization facilitates the interpretation of complex data generated by DTs, using 2D/3D representations, dashboards, graphs, and other visual tools to provide a clear and intuitive understanding of system performance [28].

The human agent plays a central role in the dynamics of DTs, which can be confirmed by the recent advances in Industry 5.0 [29], a European initiative focused on industrial transition, which places the well-being of the worker at the center of the production process and utilizes new technologies to enhance resilience, while respecting the planet's production limits. Recent studies have highlighted the role of DTs in Industry 5.0 [30], with special emphasis on the human agent, either through the proposal of an operator DT [31] or a human DT [32]. However, work is already beginning to emerge in which the human agent is seen as a community citizen [33].

2.2. Food supply chain

The FSC involves all stages, from agricultural production to food consumption. This supply chain covers food production, processing, storage, transportation, and sale, ensuring food products reach consumers safely and effectively [34]. It is also increasingly important to reintroduce food waste into the chain to close the loop, thus meeting the principles of the circular economy [35].

On the one hand, the recent emergence of crises, such as the COVID-19 pandemic and several armed conflicts, has alerted us to the need for resilient food systems capable of adapting to disruption and ensuring the continuous supply of food [1,2]. These events have highlighted vulnerabilities in FSCs, underscoring the need to reduce dependency on global/centralized supply chains and increase local production. On the other hand, the environmental impact of current food systems remains a critical concern, as they account for a third of global greenhouse gas (GHG) emissions, consume large amounts of resources, contribute to biodiversity loss, and often fail to ensure fair economic returns for stakeholders, particularly farmers [36].

Digitalization of FSCs, supported by DTs, offers promising solutions for efficient resource management, task optimization, and data-driven planning. DTs facilitate predictive analysis and optimized resource allocation [12]. For instance, they can help anticipate disruptions caused by crises, such as supply shortages or transportation bottlenecks, and propose adaptive measures to mitigate these effects [10]. Additionally, DTs improve transparency and traceability within the supply chain, ensuring compliance with safety and sustainability standards while empowering stakeholders with actionable insights for decision-making [11]. Food production and distribution can become more sustainable, secure, and resilient in the face of crises. Nevertheless, significant challenges remain, including technological asymmetries between players and territories, issues with connectivity and infrastructure, workforce training, culture shifts, and concerns related to data security, traceability, and compliance [37,38].

2.3. Smart territories

STs are geographical areas that use advanced digital technologies to improve citizens' quality of life, the efficiency of public services, and environmental sustainability. On the one hand, these territories can range from urban areas, such as smart cities [39], to rural areas, such as smart villages [40,41]. On the other hand, STs encompass large rural geographical areas, such as smart regions, where digital technologies foster the integrated development of multiple cities and surrounding rural areas [42].

STs can create synergies between rural communities and food systems by integrating innovative technological solutions. These interactions include IoT sensors and AI-driven tools to monitor crop conditions in real time, optimize agricultural production, and promote sustainable practices [43]. STs can also facilitate access to essential services, such as digital training for farmers, contributing to the modernization of the food sector and strengthening local economies

[44], with a lower environmental impact.

Despite the opportunities offered by STs, their implementation faces significant challenges, particularly in rural areas. These regions often lack comprehensive and updated data communication networks, and the population, generally older, may show less interest in digital service adoption [45]. This discrepancy complicates the creation of cooperative STs, such as smart regions, which rely on symbiotic relationships between territories that benefit from each other's synergies [46]. However, initiatives already exist that demonstrate how these barriers can be overcome, such as local programs integrating digital technologies into agricultural operations to improve productivity and rural connectivity [44].

3. Review method

A literature review should follow a structured approach and *"accumulate a relatively complete census of relevant literature"* [47]. This paper follows the approach Kitchenham [48] suggested for conducting systematic literature reviews (SLRs), as it is widely recognized for its rigor and replicability. This method was chosen over traditional narrative reviews because *"a systematic review synthesises existing work in a manner that is fair and seen to be fair"* [48]. The steps include (1) identification of research, (2) selection of studies, (3) study quality assessment, (4) data extraction and monitoring progress, and (5) data synthesis.

We selected Web of Science (WoS) and Scopus to extract the bibliographic data based on topics (i.e., title, abstract, and keywords) .[1] These two scientific databases have a wide coverage and are traditionally the most used [49,50]. Initially, we began with the search string ("digital twin" AND "regional food supply chain"), but this yielded no relevant results. Subsequently, the combination ("digital twin" AND "food supply chain" AND "region") was tested, but it also failed to identify suitable publications, ultimately defining the final search string as: (cluster A) "digital twin*"; (B) "food supply chain*"; and (C) "smart region*" OR "smart cit*" OR "smart village*" OR "smart territor*". This formulation aimed to more comprehensively capture the application of DTs in FSCs and how they are implemented in ST contexts. A total of 26, 624 manuscripts were obtained for cluster A (Scopus=16,725; WoS=8899), 10,471 for cluster B (Scopus=6506; WoS=3965), and 88, 281 for cluster C (Scopus=47,125; WoS=41,129).

The study selection process followed three criteria (SC): (SC1) manuscripts published within the last five years (2018–2023); (SC2) conference papers, journal articles, book chapters, reviews, or conference reviews; and (SC3) written in English. These criteria were applied using the mechanisms available on the web platforms of the selected bibliographic databases, and we sought to ensure that the selected studies were recent and widely accessible. Table 1 systematizes the results of the initial study selection process.

After the initial selection, we downloaded the bibliographic data for each cluster and database. The sample consisted of 96,413 records divided into six different files. We merged the data into a single file for cleaning purposes (i.e., eliminate duplicate records). A total of 76,638 articles remained after this stage, as depicted in Fig. 1, based on the three intertwined concepts of DT, FSC, and regional scale. The studies selected (IS – initial sample) and excluded according to the three criteria (EC1–3) are represented in each element of the Venn diagram. Fig. 2 shows the sample initially obtained distributed by (a) publication year and (b) type (article, book chapter, conference paper, or review).

According to the first exclusion criterion (EC1), selected manuscripts must be listed in both databases. Applying this criterion, we highlight manuscripts published in scientific sources with greater impact and that are more visible/accessible in top scientific databases. EC1 reduced the initial sample by 75 % of 19,306 manuscripts. Since our literature review aims at the interrelationship between the three concepts, we established as a second exclusion criterion (EC2) that the articles should appear in more than one cluster, i.e., belong to one of the following sets A∩B, A∩C, or B∩C (represented in Fig. 1 by the gray area). A total of 224 manuscripts accomplished this criterion. The third exclusion criterion (EC3) was created for high-quality contributions, restricting it to manuscripts published in Q1 journals or A/A* ranked conferences. We used Elsevier CiteSource for journal classification and the CORE Conference Ranking, maintained by the Computing Research and Education of Australia, to categorize top conferences. At this stage, 133 manuscripts remained. The flowchart in Fig. 3 summarizes the selection.

The final sample of 133 manuscripts included 8.3 % related to DTs and FSC (A∩B) [51–61], the popular cluster of 88.7 % addressing DTs and STs (A∩C) [62–179], and the remaining 3.0 % focusing on FSC and STs (B∩C; Fig. 1– label EC3) [180–183]. All these articles were read in full to construct and fill out the concept matrix.

The analysis process used a concept matrix as recommended by Webster and Watson [47], including the main concepts: (1) alignment with the 2030 Agenda; (2) supply chain coverage; (3) digital technologies used; (4) maturity level; and (5) adherence to Industry 5.0. To classify the selected manuscripts aligned with the 2030 Agenda [6], we listed the SDGs that each survey focused on. A similar process was used to classify the coverage of the different links in the supply chain. To identify the links in the supply chain, we used the Supply Chain Operations Reference (SCOR) model as a reference [184]. Likewise, we used the emerging and disruptive technologies for the food sector defined by Hassoun et al. [185] as a reference guide, namely Big Data (BD), ML, AI, Cloud Computing, Smart Sensors, Robotics, IoT, Blockchain, Cybersecurity, DTs, and Cyber-Physical Systems (CPS). Technology Readiness Level (TRL) and its descriptors [186] were used to classify the maturity levels, grouping the studies as a: (1) concept (TRL 1–3), corresponding to literature reviews, frameworks, and experimental proofs-of-concept; (2) development (TRL 4–6), representing the design and development of prototypes validated from laboratory settings up to demonstrations in relevant environments; and (3) deployment (TRL 7–9), indicating system prototype demonstrations in an operational environment to fully proven systems in operational settings. Regarding adherence to Industry 5.0, we searched for evidence (via keywords, descriptions, or indicators) of focus on one or more of its core pillars: (1) Sustainability, optimizing resource consumption and reducing environmental impact; (2) Resilience, the ability to withstand disruptions; and (3) Human-Centricity, prioritizing the well-being and engagement of users [29].

We then proceed to summarize the results using both quantitative and qualitative methods of analysis. On the one hand, the quantitative analysis was based on the description and characterization of the results in both textual and graphical form. On the other hand, in the qualitative analysis, we highlighted the main contributions relating to each topic by presenting concrete examples from the articles.

4. Results

This section presents the main results derived from the analysis of 133 articles, which have been systematically organized in a concept matrix available for consultation in Supplementary Material 1. The section begins with a characterization of the selected studies and a tertiary study analyzing the main literature reviews in the sample. Subsequently, the results from each of the concepts in the conceptual matrix are analyzed, namely: (1) alignment with the SDGs of the 2030 Agenda; (2) scope of the supply chain; (3) digital technologies used; (4) level of maturity; and (5) adherence to the principles of Industry 5.0. Finally, the main interrelationships between the criteria analyzed are explained.

4.1. Characterization of the selected studies

Fig. 4 details the characterization of the final sample in terms of (a) year of publication, (b) continent/country of origin, (c) type of

[1] The host institution licensing of the databases used is the b-on standard collection (https://www.b-on.pt/en/collections/).

Table 1
Summary of the initial study selection process (Source: Authors own work).

	Cluster A			Cluster B			Cluster C		
	Scopus	WoS	Total	Scopus	WoS	Total	Scopus	WoS	Total
Initial Results	16,725	8889	25,624	6506	3965	10,471	47,152	41,129	88,281
SC1	16,534	8810	25,344	4348	2603	6951	37,233	31,222	68,455
SC2	16,238	8627	24,865	4242	2562	6804	36,227	30,572	66,799
SC3	15,329	8512	23,841	4146	2535	6681	35,635	30,256	65,891

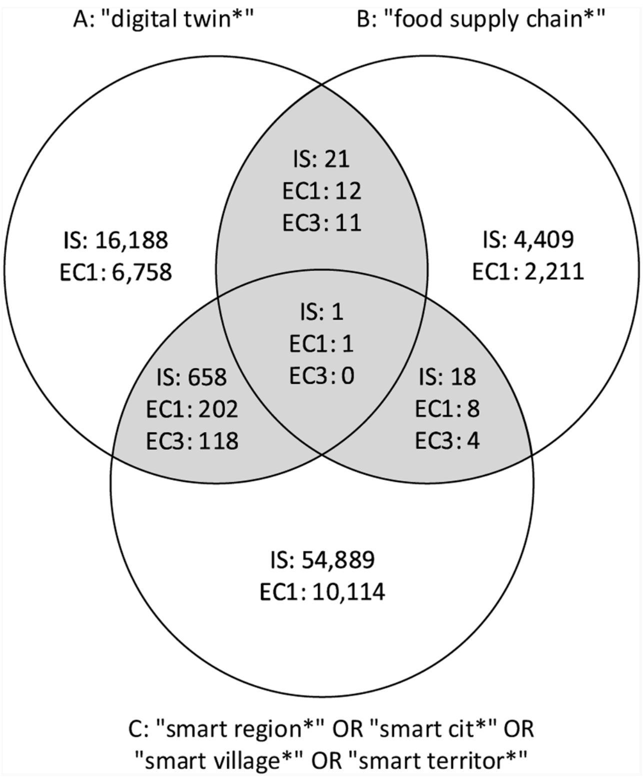

Fig. 1. Sample distribution at different stages of the study exclusion process (Source: Authors own work).

publication, and (d) publisher/journal.

Most articles (65.7 %) were published in the last two years (2023=38.1 %; 2022=27.6 %), indicating the emerging and growing nature of this field. This can be attributed to the growing global focus on digital transformation and sustainability, driven by advances in Industry 5.0 and the urgent need to address challenges in supply chains, which recent global crises have exacerbated. Two continents, Asia and Europe, have contributed 44.0 % and 39.6 % of the studies, respectively, with China leading the list of countries (14.9 %). The origin was extracted from the affiliation of the first author.

A large number (81.3 %) are journal articles, 16.4 % reviews, and the remaining 2.2 % book chapters or conference papers (1.5 % and 0.7 %, respectively). In terms of publication source, 35.1 % of the manuscripts were published by MDPI, 23.9 % by Elsevier, 17.9 % by IEEE, and the remaining 23.1 % by other publishers; Open access publications, namely Sustainability and IEEE Access have a higher number of publications (8.2 % and 7.5 %, respectively), which may reveal a practice-oriented approach to research in this domain.

4.2. Tertiary study

Literature reviews are essential in the initial stages of technology or concept development, aiming to understand how researchers approach the phenomenon and identify future work opportunities. A total of 17 systematic literature reviews were identified as being more closely related to the purpose of our study, with 3 adopting a broad perspective, 10 focusing on the smart city context, and 3 being more specific to the FSC.

DTs can represent different layers of an urban area. For example, the composition of more simple elements like buildings or vehicles into a coherent whole that is evaluated at the city level to support decisions, or

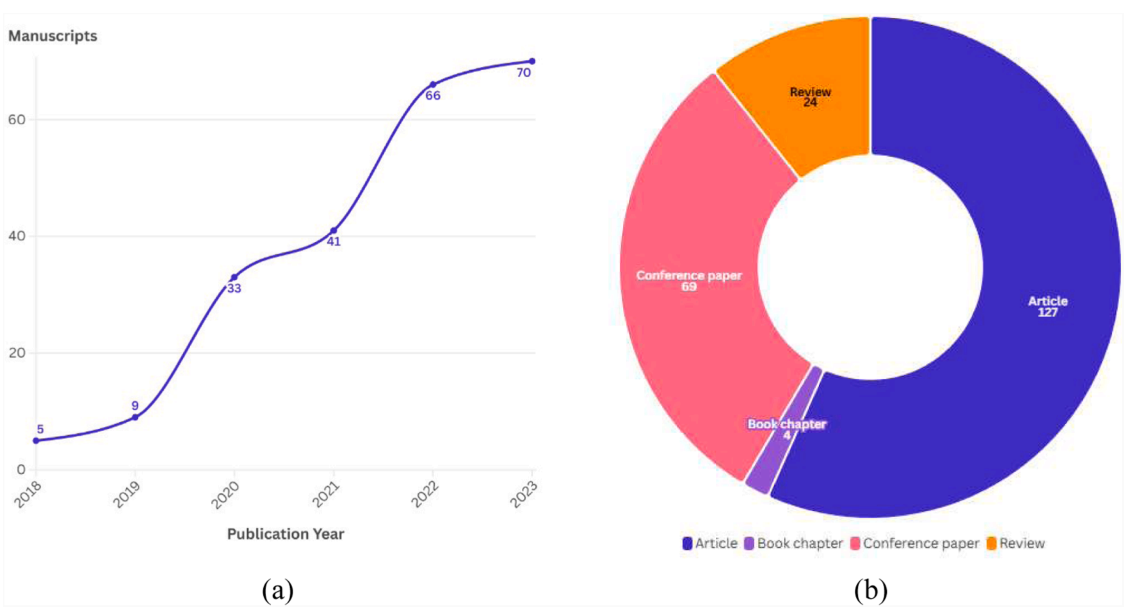

Fig. 2. Distribution of initial studies by (a) year of publication and (b) type of publication (Source: Authors own work).

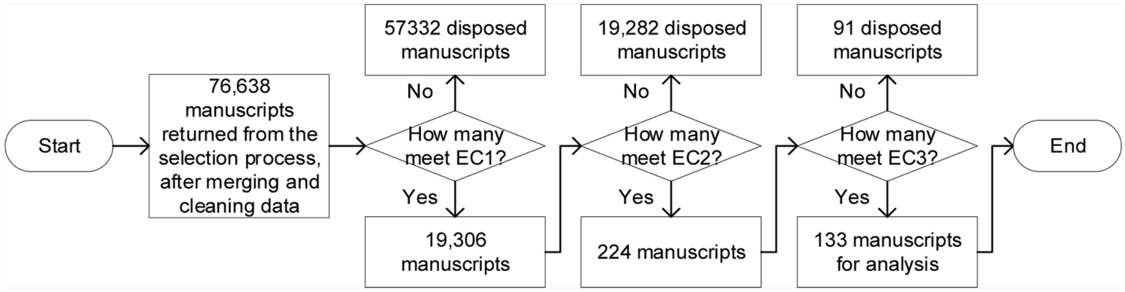

Fig. 3. Summary of the study selection process (Source: Authors own work).

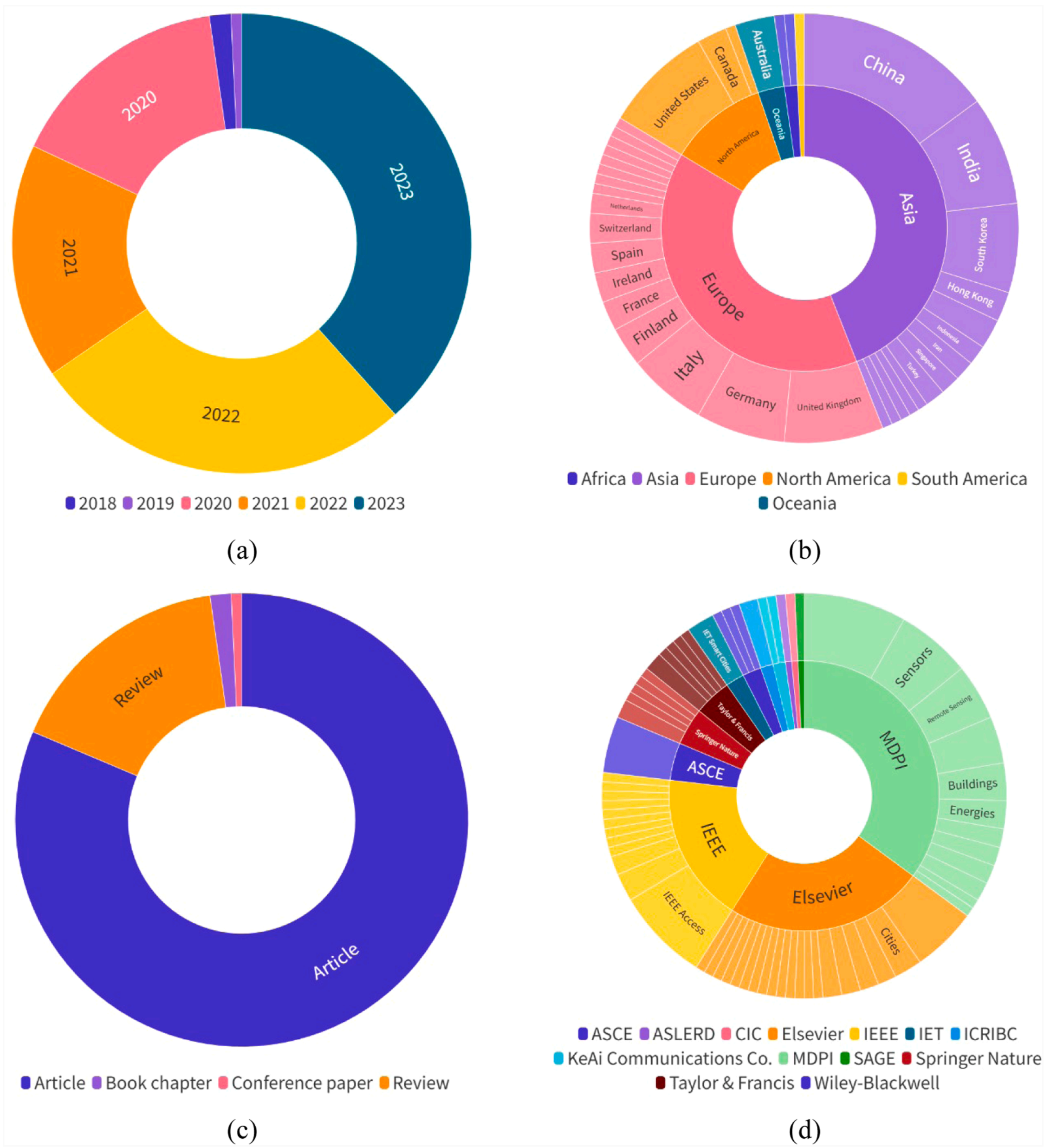

Fig. 4. Characterization of the sample with the respect to (a) year, (b) origin, (c) type, and (d) source of the publication (Source: Authors own work).

even in situ, where users access the DT to obtain information related to the location [73]. In the built environment, DTs can go beyond the mere representation of buildings and assist in the entire lifecycle from construction to real-time monitoring and optimization, or urban planning, assisting policymakers with simulation capabilities [74,115] but it is also possible to include layers of social and economic aspects of city development, like movement patterns or health quality prediction (e.g., air quality measures, traffic, and people movements) [105]. A more technical perspective of communication infrastructure for smart cities was selected by Liu and Yang [64] and Wu et al. [110], revealing the challenges of obtaining and transmitting the large volumes of data needed to monitor the city environment and simultaneously enabling bi-directional interaction (e.g., actuators, based on data analysis for optimization).

One of the most extensive and recent reviews on the topic [91] highlights transportation, energy, environment and resources, public management and planning, city services, healthcare, buildings, education, and economic indicators as key application areas, which are aligned with the review presented by Mylonas et al. [69]. More specific reviews can be found in a few of these main clusters, namely in energy [69,170], and resiliency/risk management [97,108,135]. Curiously, the FSC was not yet at the top of priorities. The four challenges identified by Wang et al. [65], including computing power, interoperability, privacy, and security, confirmed that *"few studies combine a DT with analysis methods to make integrated decisions"* and require additional research to shift the conceptual nature of city DTs to actual applications that allow impact assessment. Several examples of city DTs can be found in the work of Botín-Sanabria et al. [109]. Still, it is also possible to identify a narrow focus of sustainability in (1) air pollution or (2) reducing energy waste, missing the entire range of opportunities to use DTs in social (e.g., assist the protection of the elderly or homeless population) and economic facets of sustainability.

Considering the enormous advances in adopting DTs in manufacturing supply chains [127], more studies are necessary to understand adoption in broader geographical areas like cities or regions. Our sample includes three examples of reviews that address the case of FSCs. For example, DTs can provide supply chain *"visibility, minimizing bottlenecks, planning for contingencies, and improving existing processes and resources"* [52] and improve food security [57] or be combined with other technologies like blockchain [59]. Most reviews emphasize the emergent nature of DTs in intelligent spaces and supply chains, aiming to categorize the research by application types and outline the benefits and challenges of adopting the concept. One of the main gaps identified is the need to understand local FSCs and the specific characteristics of the circular economy in cities or regions.

4.3. Alignment with the 2030 agenda

The 2030 Agenda for Sustainable Development, adopted by all United Nations Member States in 2015, establishes global sustainable development priorities for 2030, aiming to mobilize global efforts through a set of common goals and targets. These goals develop a common language for all stakeholders, setting sustainability targets on critical areas of humanity, and are organized around five principles: (1) *Planet*, i.e., protect our planet's nature resources and climate for future generations; (2) *People*, i.e., eradicate poverty and hunger in all its forms and ensure dignity and equality; (3) *Prosperity*, i.e., ensure a prosperous and balanced life in harmony with nature; (4) *Peace*, i.e., promote peaceful, just and inclusive societies; and (5) *Partnership*, i.e., implement the agenda through a strong global partnership [6].

The 2030 Agenda consists of 17 SDGs: (1) No Poverty; (2) Zero Hunger; (3) Good Health and Well-Being; (4) Quality Education; (5) Gender Equality; (6) Clean Water and Sanitation; (7) Affordable and Clean Energy; (8) Decent Work and Economic Growth; (9) Industry, Innovation and Infrastructure; (10) Reduced Inequalities; (11) Sustainable Cities and Communities; (12) Responsible Consumption and Production; (13) Climate Action; (14) Life Below Water; (15) Life on Land; (16) Peace, Justice and Strong Institutions; and (17) Partnerships for the Goals [6]. Fig. 5 shows two graphs: (a) contributions to achieving the SDGs, grouped by dataset; and (b) the relationship between them.

The selected manuscripts are closely aligned with the 2030 Agenda: all of them have at least one SDG, 73.9 % have two or more, 32.9 % have three or more, and a small percentage (3.0 %) reach four different SDGs. However, we found a gap in papers focusing on SDG 1 (No Poverty), SDG 5 (Gender Equality), SDG 14 (Life Below Water), SDG 15 (Life on Land), and SDG 17 (Partnership for the Goals). One possible reason is that DT-based solutions are often developed in technologically advanced or economically stable regions (64.93 % of the studies analyzed come from advanced economies according to the latest IMF data [187]), thus overlooking some global challenges such as poverty or hunger. Hence, future research could explore how these digital solutions might be adapted to areas with more acute socio-economic vulnerabilities.

In contrast, most of the works analyzed aimed to contribute to achieving SDG 11 (Sustainable Cities and Communities) and SDG 9 (Industry, Innovation, and Infrastructure), with percentages of 85.1 % and 60.4 %, respectively. Interestingly, 51.5 % of the articles aimed to contribute to the achievement of both SDGs simultaneously. The relationships between SDG 9 and SDG 12 (Responsible Consumption and Production), SDG 11 and SDG 12, and SDG 7 (Affordable and Clean Energy) and SDG 11 are also evident, being present in 13.4 %, 11.9 %, and 10.4 % of the analyzed articles, respectively.

The SDG focus is valid when analyzing each cluster separately, but

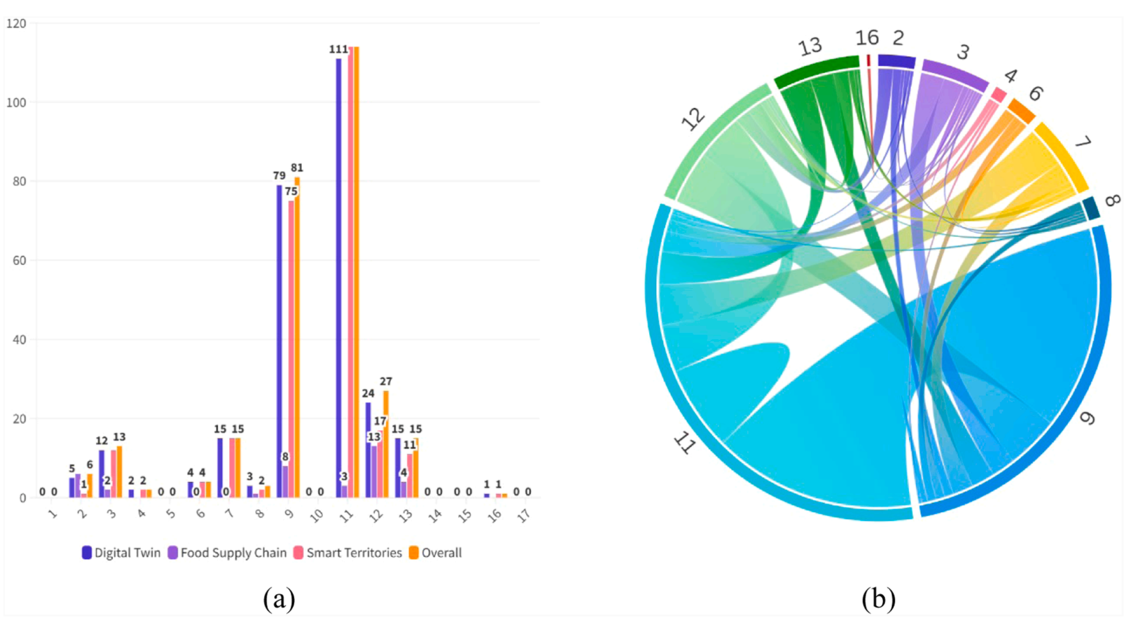

Fig. 5. (a) Alignment with the 2030 Agenda, grouped by dataset; (b) Interrelationship between them (Source: Authors own work).

some singularities exist. In the FSC studies (cluster B), SDG 12 has the highest number of studies (86.7 %), whereas SDG 11 has the fifth-highest number of studies (20.0 %), the second most aligned SDG. No studies were found in this cluster that contributed to the achievement of SDG 4 (Quality Education) or SDG 16 (Peace, Justice, and Strong Institutions), in addition to the aforementioned SDGs (1, 5, 10, 14, 15, 17).

Only 4.5 % of the articles (6) addressed SDG 2 (Zero Hunger), which faces significant challenges, including stagnation in global progress [188]. There are contributions for sustainable food production systems [51–53,55,56,181], resilient agricultural practices that increase productivity and production and protect ecosystems [51–53], and the provision of safe and nutritious food throughout the year [55,57,181]. These goals are directly relevant to RFSCs and crucial in ensuring food security and regional sustainability.

SDG 6 (Clean Water and Sanitation), although still relatively unexplored, holds promising applications in DTs for regional water systems. They can improve water quality by reducing pollution and eliminating the disposal of hazardous materials [75,124,156]. Examples include using DTs to manage water distribution networks, as in the study by Conejos Fuertes et al. [131], which optimized operations in Valencia using simulations and real-time data. These approaches are transferable to RFSCs in efficiently managing water resources, which are fundamental to sustainable agricultural production.

SDG 11 (Sustainable Cities and Communities) is widely addressed in the studies analyzed (84.9 %), offering transferable contributions to RFSCs, such as promoting more efficient and sustainable logistics systems. DTs can reduce carbon emissions and improve urban mobility by optimizing logistics operations [80,173]. In addition, they facilitate traceability and the management of local infrastructures, contributing to better integration of rural and urban areas [104]. These capabilities help to strengthen local economies and promote the sustainability of RFSCs.

SDG 12 (Sustainable Production and Consumption), relevant to 20.3 % of the studies (27), presents targets aligned with RFSCs, such as reducing food waste and promoting sustainable agricultural practices [55,57,181]. DTs can optimize logistics processes and manage supply chains efficiently, reducing losses and encouraging the consumption of local products. These practices reinforce the sustainability of RFSCs and increase the resilience of regional communities.

Most of the studies analyzed come from developed countries, where the debate tends to focus on trends linked to industrialization, innovation, and infrastructure (SDG 9) and sustainable cities (SDG 11), reflecting the priority given to more industrialized sectors and improvements to the urban fabric. On the other hand, less attention is paid to SDGs that address the most pressing social and environmental challenges facing developing nations, such as poverty eradication (SDG 1), hunger (SDG 2), gender equality (SDG 5), reducing inequalities (SDG 10), underwater life (SDG 14), terrestrial life (SDG 15), and global partnerships (SDG 17). Therefore, the researcher's context may influence the priorities selected for their work. As the Sustainable Development Report 2023 [188] states, *"At the midpoint of the 2030 Agenda, all of the SDGs are seriously off track"*, which reinforces the need for research that includes these underexplored SDGs and expands knowledge about inclusive solutions to integrate demands from different socio-economic contexts.

4.4. Supply chain coverage

The SCOR model is a set of tools for evaluating and comparing supply chain activities and performance to help organizations make rapid and transformational improvements to drive end-to-end supply chain management. Developed by the Association for Supply Chain Management (ASCM) in 1996 to describe the business activities associated with all phases of satisfying customer demand, the model has been regularly updated to reflect changes in supply chain business practices. Currently, the SCOR model describes the supply chain in six key processes: (1) *Plan*, which involves the creation of a plan for operating the supply chain; (2) *Order*, which is associated with the customer's purchase of products and services; (3) *Source*, which includes activities associated with sourcing, ordering, scheduling the ordering, delivering, receiving, and transferring products and/or services; (4) *Transform*, which is associated with the planning and production of products and services; (5) *Fulfill*, which is associated with the fulfillment of customer orders for products; and (6) *Return*, which is associated with the reverse flow of goods or services (circular activities) [184].

Fig. 6 shows the distribution of the articles, grouped by datasets, (a) focusing on each process of the SCOR model, as well as (b) their relationship.

Most processes of the SCOR model are covered in the literature, except Order. A total of 63.43 % of the articles focus on the Fulfill process, which is the most focused process in the sample. The Transform process accounts for 46.27 %, followed by Plan at 26.87 %, Source at 20.33 %, and finally Return at 10.45 %. Almost all articles focus on only one of the major processes of the SCOR model, with the Transform and Fulfill processes being the ones that do not maintain relationships with other processes (37.10 % and 30.59 %, respectively). On the other hand, 52.98 % of the articles focus on more than one SCOR process, with the strongest relationships between the Transform-Fulfill and Plan-Fulfill process (both present in 16.41 % of the articles analyzed). Additionally, 12.68 % of the analyzed articles incorporate elements from three or more SCOR model processes, and 11.76 % of these articles specifically focus on four of the six SCOR model processes.

Maheshwari et al. [54] use DTs to optimize real-time planning, monitoring and control process in the FSC, focusing on four SCOR model processes: Plan, by integrating sourcing, production, and distribution strategies through agent-based simulations and linear programming for flexible planning; and Source, Transform, and Fulfill, by digitally implementing these strategies to improve synchronization between suppliers, production, and delivery. This results in efficient resource utilization, reduced cycle times, and a 94 % service level, achieved through the optimization of equipment and materials. Liu et al. [61] also addresses four SCOR model processes: Source, by using sensors and IoT to improve resource acquisition and monitoring in agricultural supply chain; Transform and Fulfill, by applying AI and robotics to enhance production and distribution logistics, improving traceability and the food quality; and Return, by employing BD and Blockchain for better waste management and recycling.

Two works, Yossef Ravid and Aharon-Gutman [85] and Boulanger [100] selected a different perspective. The first article introduces the concept of the Social Urban DT, integrating sociological and technological data to enhance urban management and social planning. The main focus is on urban issues, while the second article presents a bibliometric analysis of smart city strategies post-COVID-19, highlighting technological innovations and urban adaptations, but does not directly address supply chain management or SCOR processes.

4.5. Enabling technologies

The Fourth Industrial Revolution (4thIR) has a strong impact *"on customer expectations, on product enhancement, on collaborative innovation, and on organizational forms"* [189]. It extends beyond simple digitalization to innovation based on the combination of technologies. Among the various emerging digital technologies, we considered those identified by Hassoun et al. [185] for our study, as they have the most significant impact on the food sector. Fig. 7 shows (a) the uptake of digital technologies that support the 4thIR distributed by dataset, as well as (b) the interrelationships between them.

As expected, DT technology is present in 96.3 % of the studies since it is one of the search terms. This is followed by IoT, AI, and BD with a representation of 79.1 %, 75.4 %, and 73.9 %, respectively. On the one hand, the least used technologies are Robotics and Blockchain (2.2 % and 8.2 %). All the articles analyzed use at least two digital technologies, 96.3 % use three, 78.4 % use four, 53.8 % use five, 29.2 % use six, 14.3 %

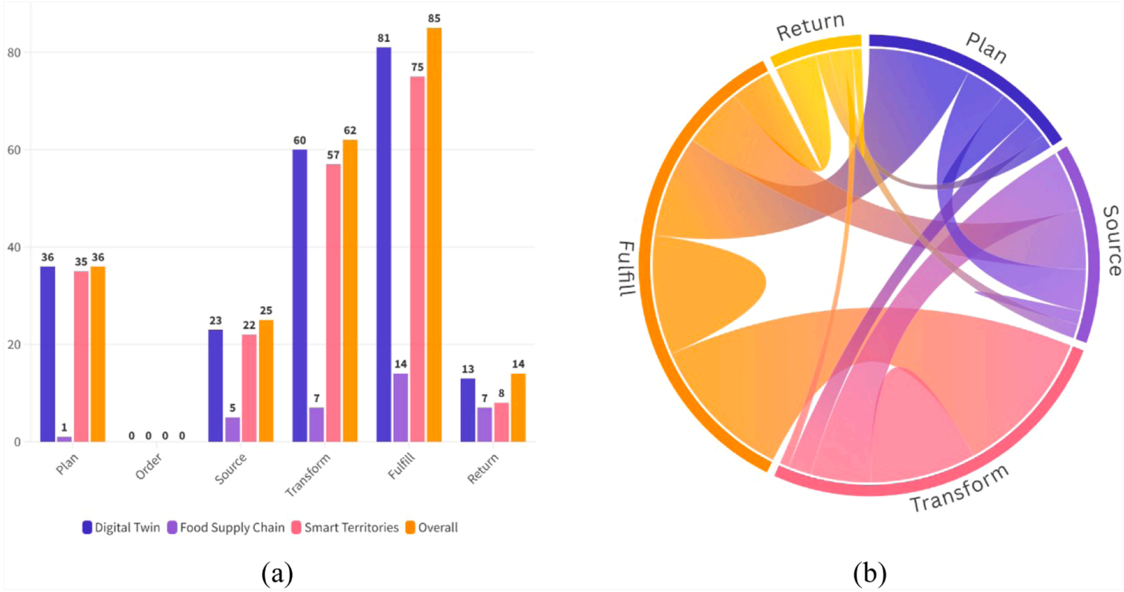

Fig. 6. (a) Coverage to SCOR model processes, group by dataset; (b) Interrelationship between them (Source: Authors own work).

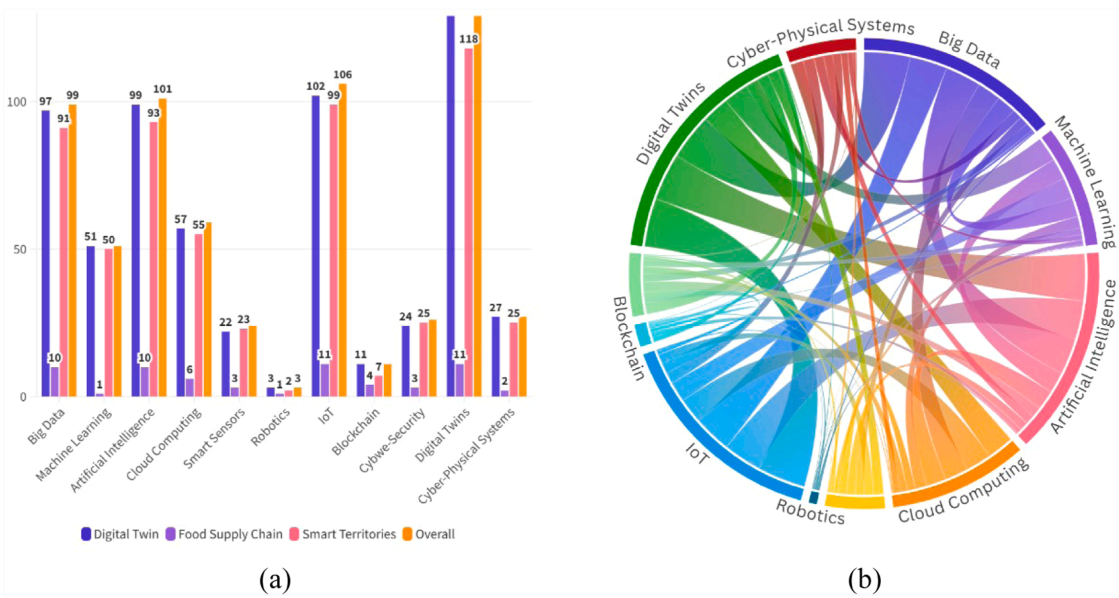

Fig. 7. (a) Adoption of technologies that promote the 4thIR, grouped by dataset; (b) Interrelationship between them (Source: Authors own work).

use seven, and 3.0 % use eight. The most common combinations are DT-IoT, DT-AI, and DT-BD, which are used 101, 98, and 96 times, respectively. Of the combinations that do not involve DTs, the most usual are IoT-AI, IoT-BD and AI-BD with 80, 78 and 75 occurrences, respectively. In contrast, Robotics-Cybersecurity and Robotics-CPS are not used together.

Chen et al. [81], Shirowzhan et al. [74] and He et al. [95] explore various digital technologies critical to the 4thIR in smart cities: (1) the integration of DTs and IoT to create a distributed sensor infrastructure that enhances real-time urban monitoring and response; (2) BD and CC to manage and analyze large volumes of data generated by sensors, and (3) ML and AI for advanced interpretation of this data to improve the efficiency and automation of urban responses. In the same context, Callcut et al. [124] examines the implementation and use of DTs for civil infrastructure. These authors explore Cybersecurity as a critical element and emphasize the need to protect complex data networks that underpin DTs.

Although the Metaverse and related technologies (AR, VR, and XR) are not included in the list that we used as a reference guide, a notable body of studies is available. Li et al. [146] studies the use of XR technologies in mechanical stress experiments for underground pipes, focusing on enhancing human-computer interaction and spatial perception in these experiments. Michalik et al. [90] use VR and DT to improve the acceptance of technological innovations in smart cities, while Hasan et al. [107] selected AR and VR for construction machinery. Li et al. [121] integrate IoT with Metaverse, focusing on the convergence of physical and cyber worlds through AR and VR applications, supported by responsible AI, high-speed data communication, low-cost edge computing, and DT. Aloqaily et al. [139] propose a DT-enabled Metaverse system that integrates AR, VR, 6 G communication networks, Blockchain, and AI to create a high-quality immersive experience and efficient resource management. Seo et al. [159] propose a digital forensic investigation framework for the Metaverse by incorporating VR, Blockchain, and other technologies to address virtual crimes and security issues on this new platform. Casini [160] explores the application of XR to the operation and management of smart buildings, highlighting the potential for improving energy efficiency and infrastructure management through digital models and advanced data interaction.

Of the 134 articles analyzed that make up the literature review sample, only five do not focus on DTs. For example, Samak et al. [112] explore BD, AI, CC, Robotics, and IoT by developing and demonstrating an integrated ecosystem for research and innovation in autonomous driving using a combination of virtual simulation, physical prototyping, and networked software. Another example is the work of Ullah et al. [180], which explores applications of Blockchain technology in sustainable smart cities, addressing FSCs, tourism, smart transportation, energy management, telecommunications, and smart healthcare systems, with an emphasis on data security, automation, and efficient resource management. Additionally, examining an IoT-based supply chain management model, the work of Nagarajan et al. [181] optimizes dynamic vehicle routing using ant colony algorithms and CC to enhance efficiency and traceability in sustainable smart cities. In this spirit of sustainable smart city management, Leyerer et al. [182] develop a multi-level optimization model to enhance the efficiency of supermarket delivery systems (BD, AI) by utilizing refrigerated lockers and electric cargo bikes (IoT), thereby reducing emissions and urban traffic. Finally, a study by Thibaud et al. [183] focuses on the integration of network technologies such as IoT in high-risk Environment, Health and Safety industries, highlighting their potential to improve safety and operational efficiency through real-time decision support systems.

4.6. Maturity level

Evaluating the maturity of research is crucial for understanding its readiness for practical application and informing decision-making related to investments. Several tools can be used to quantify the maturity of technology, with the TRL scale being one of the most widely used. This mechanism was conceived in the 1970s by NASA as *"a systematic metric/measurement system that supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology"* [190]. This scale assesses the maturity of technology at nine different levels, from basic principles observed (TRL 1) to an actual system proven in an operational environment (TRL 9). Since 2012, the European Commission (EC) has used this scale as a reference to determine the development or maturity of research [186].

Fig. 8 shows the level of research maturity of the analyzed research papers grouped by key concept and overall, in the form of a stacked bar chart.

Most works analyzed are at a low level of maturity, with 54.47 % at a conceptual stage (TRL 1–3), 38.06 % at the development stage (TRL 4–6), and the remaining 7.46 % already at an advanced stage of deployment (TRL 7–9). This trend is transversal when analyzing the different datasets separately and their combinations. There is, however, an exception in subset FSC∩ST, where 50 % of the research is at an early stage, and the remaining 50 % is in the development phase (yet, this set consists of only four publications).

The articles we have classified as being in a conceptual stage (TRL 1–3) are (1) review articles, (2) frameworks/research agendas, or (3) experimental proof of concepts, as they only document basic principles and/or formulate technological concepts. For example, Henrichs et al. [56] present a literature review and classification of DT applications in the food industry, identifying both challenges and potential opportunities. Another example is the work of Wang et al. [65], which discusses theories and preliminary models of desiring production and DTs. Relevant contributions can be found in this sample [68,70,77,94,142,145,150], not addressing practical implementations or empirical validations.

Articles in the development stage (TRL 4–6) include validation of the technology in either a laboratory or a relevant environment, as well as demonstrations of the technology in a semi-industrial setting. For example, White et al. [79] uses a detailed digital model to simulate real-world scenarios such as flooding and crowd movement, and includes the collection and analysis of real-world data to improve the accuracy of simulations and emergency response. Another example is the work of Xue et al. [163], which implements and validates an automated method for detecting and classifying urban objects in LiDAR point clouds, or Li et al. [165], which proposes and experimentally validates a method for fusing images and point clouds from area platforms, mobile mapping systems, and backpacks for optimized 3D mapping in urban areas, demonstrating its effectiveness in real-world scenarios. Ono et al. [148] propose and simulatively validate the AMoND method for reducing network traffic in mobile ad hoc networks, demonstrating its effectiveness in reducing control messages and maintaining packet arrival rates. By using real data and simulations to create DTs, the work of Fan et al. [122] informs urban planning and infrastructure decisions. Also, research by Binsfeld and Gerlach [60] implements and validates the architecture of a DT to optimize the FSC through simulations based on real data, providing decision support tools for real-world users.

Finally, the research projects that we classified as being at the deployment stage (TRL 7–9) demonstrated the prototype system in an

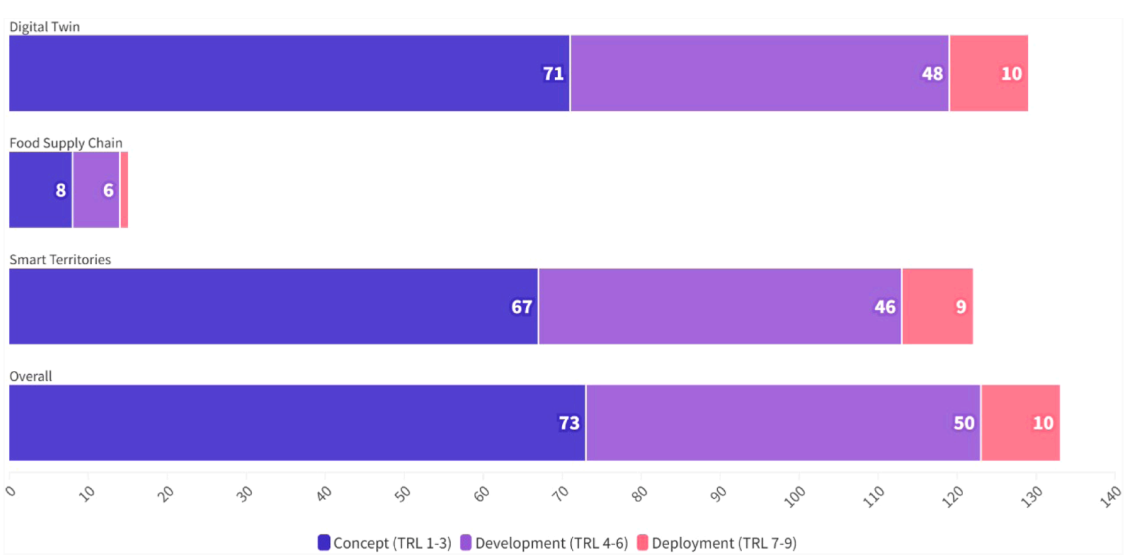

Fig. 8. Maturity level, group by dataset (Source: Authors own work).

operational environment, completed and qualified projects, or projects that were proven in an operational environment. These account for only 7.5 % of the sample under analysis. The work of Dembski et al. [86] implements and validates urban DTs in a real collaborative and participatory planning process in Herrenbery, Germany, involving stakeholders and citizens in VR and AR environments. Artopoulos et al. [137] implement the PERIsCOPE platform to monitor and assess the state of conservation of historic buildings using earth observation technologies and non-destructive testing, validating its effectiveness in two study sites on the island of Cyprus with real data and stakeholder feedback. The work of Zhang et al. [147] is also in the deployment phase, as it validates and demonstrates the effectiveness of the AID-Fire system in full-scale fire tests, using IoT sensor data, a cloud server, and a user interface to identify and predict fire scenarios in real-time. The work of Lohman et al. [174] involves the practical implementation and testing of the IMB framework in a real case study in Amsterdam, demonstrating its effectiveness in answering urban planning questions. We conclude with an example applied to the FSC, where Accorsi et al. [58] Use DTs to simulate and validate transport flows in food distribution networks across Italy, using primary data, sensitivity analyses, and optimizing logistical and environmental processes.

A parallel can be drawn between the common barriers and challenges encountered in advancing through the TRL scale and what Nunamaker et al. [191] called the *"last research mile"*. *"The last research mile proceeds in three stages: proof-of-concept research to demonstrate the functional feasibility of a solution; proof-of-value research to investigate whether a solution can create value across a variety of conditions; and proof-of-use research to address complex issues of operational feasibility. The last research mile ends only when practitioners routinely use a solution in the field"* [191]. As TRLs progress from early proofs of technical feasibility (TRL 1–3) to development (TRL 4–6), and full deployment (TRL 7–9), organizations often confront new operational, political, and human-centric barriers that purely technical prototypes cannot anticipate. By recognizing that *"the devil is in the details, and the details are in the field"* [191], researchers and practitioners gain practical guidance for designing solutions that extend beyond mere proof-of-concept and endure in operational settings, ensuring long-term impact and relevance.

4.7. Adherence to industry 5.0

In July 2020, a group of experts from research and technology organizations discussed the concept of Industry 5.0 in two virtual workshops facilitated by the EC and came up with the following definition: *"Industry 5.0 recognises the power of industry to achieve societal goals beyond jobs and growth to become a provider of prosperity, by making production respect the boundaries of our planet and placing the wellbeing of the industry worker at the centre of the production process"* [29]. In contrast to Industry 4.0, which focuses on CPS and IoT, Industry 5.0 is based on supporting and promoting socially and environmentally relevant values [29], of which we can highlight three main elements: (1) *Sustainability*, i.e., reduce energy consumption and emissions to preserve resources for future generations while meeting current needs; (2) *Resilience*, i.e., industrial production needs to be more robust to handle disruptions and support critical infrastructures during crises; and (3) *Human-Centricity*, i.e., the production process should prioritize basic human needs and interests over technology [8].

Fig. 9 provides an overview of how the analyzed studies adhere to the key elements of Industry 5.0, both in terms of (a) their distribution by topic under investigation, and (b) their general interrelationship.

The sample aligns closely with the principles of Industry 5.0, with 56.72 % of the studies focusing on its three core elements, 27.61 % focusing on two, 14.18 % focusing on one, and only 1.49 % [155,179] selecting a different perspective. Of the three core elements, Sustainability is a priority in almost all of the articles analyzed (97.01 %). Still, the other elements are also highly prevalent, with 72.39 % for Resilience and 70.14 % for Human-Centricity.

Of the 14.17 % of articles that adhere to only one of the pillars of Industry 5.0, 94.74 % focus on Sustainability, and the remaining 5.26 % on the Resilience pillar. One of the examples of the first group is the research conducted by Ozturk [151], which focuses on the use of DTs to optimize the lifecycle management of buildings, promote energy efficiency, reduce waste, and improve the sustainability of buildings over time. Another example that focuses only on the Sustainability pillar is Kim and Ben-Othman [132], who propose a security monitoring framework that maximizes the participation of low-resource and reusable devices, reducing costs and environmental impact, instead of relying on new, high-resource devices. As for the second group (Resilience), Seo et al. [159] propose digital forensics framework for the Metaverse that addresses data collection, analysis, and secure storage,

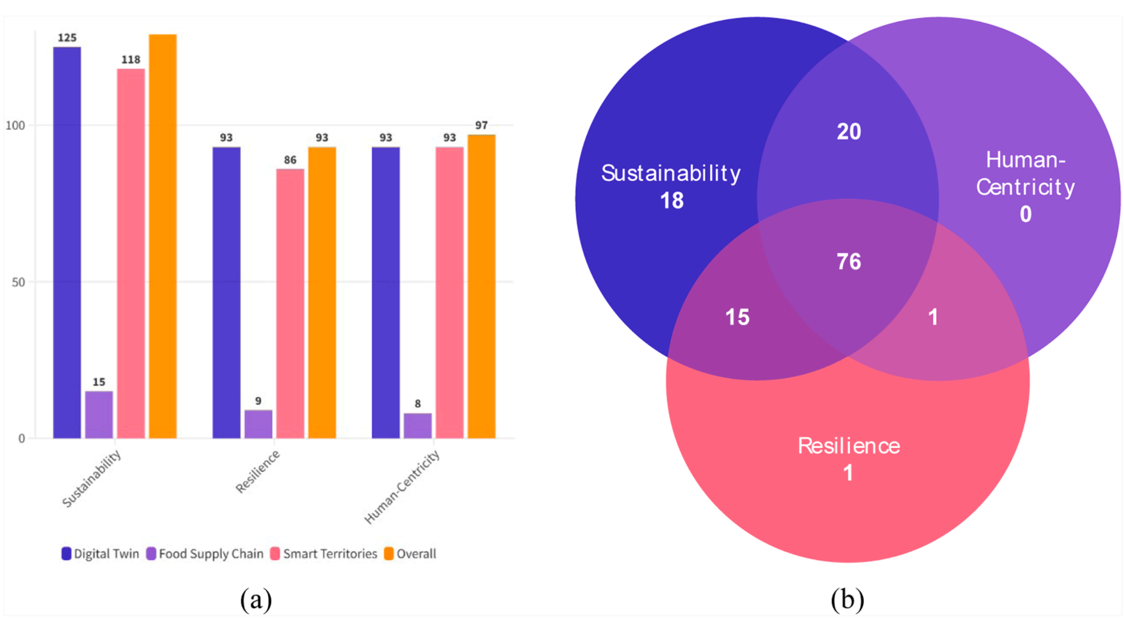

Fig. 9. (a) Adherence to Industry 5.0 principles, grouped by dataset; (b) Interrelationship between them (Source: Authors own work).

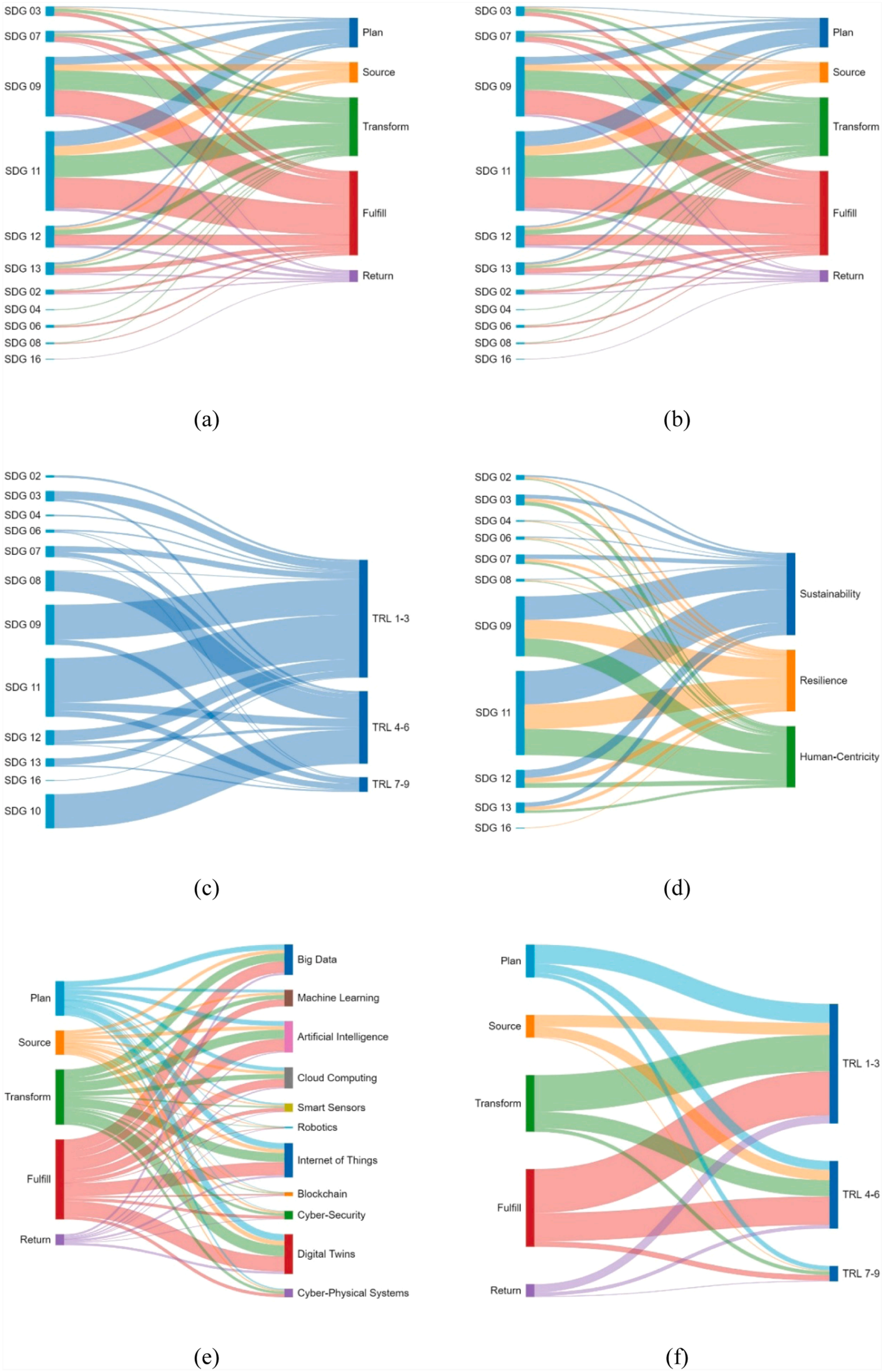

Fig. 10. Alluvial graphs of the interrelationships between concepts (Source: Authors own work).

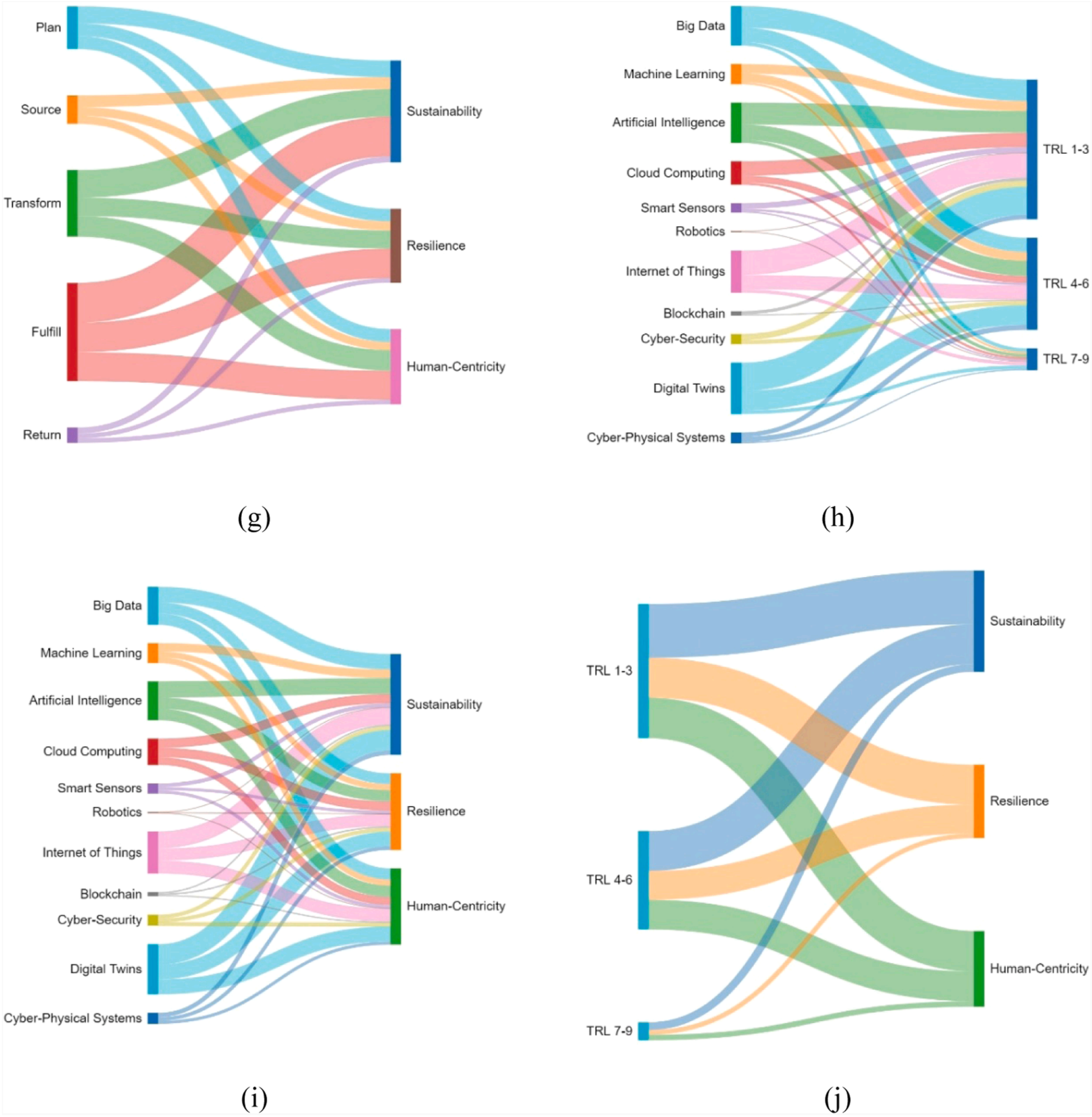

Fig. 10. (*continued*).

ensuring the integrity of evidence and the ability to respond to cybercrime in a complex and interconnected digital environment.

37 articles focus on two of the three pillars of Industry 5.0. The strongest relationship is between Sustainability and Human-Centricity, which corresponds to 54.05 % of the articles in this subgroup. An example is the work of Steinmetz et al. [130], which uses DTs to optimize the management of car services, promote resource efficiency, and provide users with a personalized experience based on detailed analyses of data and behavior. Aloqaily et al. [139] is one of the few articles that adheres exclusively to the pillars of Resilience and Human-Centricity (2.71 %), as it integrates DTs with advanced technologies such as 6 G, Blockchain, and AI to provide a continuous and interactive Metaverse environment that supports the resilience of communication and the centrality of human through an immersive and personalized experience.

Many studies (58.96 %) aim to provide a complete response to the current challenges of the new industrial paradigm (Industry 5.0) by developing a human-centered approach, sustainability, and resilience. Since it is not possible to explain in detail how all the articles analyzed align with the three central pillars of the Industry 5.0 principles, we present three illustrative examples below. The first is the work by Xia et al. [80], which integrates BIM and GIS technologies for the sustainable design of smart cities, promotes resilience through efficient urban management and focuses on human-centricity by enhancing the quality of urban life. The second example Ferré-Bigorra et al. [120], who use DTs to plan more sustainable and resilient cities, promoting human-centeredness by involving citizens in urban management. Finally, Human et al. [126] developed a framework for DT systems that promotes sustainability by optimizing industrial processes, resilience by being able to adapt and respond quickly to changes, and human-centeredness by considering the needs and interaction of the users in the design of the system.

DTs in Industry 5.0 necessitate a thorough evaluation of the trade-offs between sustainability, resilience, and human-centricity, as maximizing one dimension can compromise the others. Practices that favor sustainability can require significant investments and limit the operational agility essential for resilient responses to crises. At the same time, a strict human-centric approach can increase the complexity of systems and operating costs, affecting efficiency and environmental viability. Consequently, systemic planning must be adopted to define clear indicators for each dimension and incorporate modular and adaptable technologies. This implies conducting cost-benefit and socio-environmental impact analyses at all stages, enabling dynamic adjustments based on real-time data. For researchers, further studies are necessary to understand how DT implementations can promote synergies among the three pillars of Industry 5.0, necessitating a multidisciplinary approach. For practitioners, Industry 5.0 *"offers new opportunities to compete with social innovation, but there is a trade-off. The industry will require more physical-digital convergence and must prepare its investments for the possibility that Industry 5.0 will become increasingly – positively – intrusive in company data and decision-making processes at a more fine-grained level than ever, putting DT deployments at the top of digital transformation priorities"* [30].

4.8. Interrelationships between concepts

Fig. 10 shows the interrelationship between the various concepts presented above in the form of alluvial graphs, namely: (a) 2030 Agenda and SCOR Model; (b) 2030 Agenda and 4thIR technologies; (c) 2030 Agenda and maturity level; (d) 2030 Agenda and Industry 5.0; (e) SCOR Model and 4thIR technologies; (f) SCOR Model and maturity level; (g) SCOR Model and Industry 5.0; (h) 4thIR technologies and maturity level; (i) 4thIR technologies and Industry 5.0; and (j) maturity level and Industry 5.0.

Fig. 10a, which relates the SCOR Model processes to SDGs, reveals interesting trends. Firstly, it is clear that the Transform and Fulfill processes are the most frequently associated with the SDGs, with 135 and 194 occurrences, respectively. SDG 11 (Sustainable Cities and Communities) stands out with the highest number of associations, totaling 183, mainly in the Plan, Transform, and Fulfill processes. This suggests a strong link between the creation of STs and the implementation of sustainable strategies in the supply chain. In addition, SDG 9 (Industry, Innovation and Infrastructure) also has a significant number of occurrences (137), especially in the Plan, Transform and Fulfill processes, reinforcing the importance of industrial innovation in building more efficient and sustainable supply chains. In contrast, objects such as SDG 1 (No Poverty), SDG 5 (Gender Equality), SDG 10 (Reducing Inequalities) and SDG 14 (Life Below Water) have little or no correlation with the SCOR Model processes, suggesting areas where there is still potential for development and integration with digital and intelligent supply chains.

Fig. 10b correlates the leading digital technologies of the 4thIR with the SDGs. The alluvial graph indicates that most technologies are strongly associated with SDGs 9 and 11, with 393 and 542 occurrences, respectively. Among the technologies, DTs and IoT are particularly prominent, with 269 and 224 occurrences, respectively, underscoring their fundamental role in driving digital innovation and fostering the development of smart cities. In addition, BD and AI also have a significant presence, especially in SDG 11, suggesting that BD analysis and intelligent automation are key to creating sustainable communities. In contrast, Robotics and Cybersecurity show fewer overall correlations, indicating that, although necessary, these technologies still have potential that has not been fully exploited in relation to the SDGs. This analysis highlights the central importance of emerging technologies in the transformation and sustainability of STs and FSCs.

Fig. 10c reveals important insights into the stage of progress of the research associated with each SDG. SDG 11 stands out once again with the highest number of occurrences across all maturity levels, totaling 114, with a significant distribution at the concept (60), development (46), and deployment (8) levels. This indicates a strong focus on innovation to improve sustainable cities and communities. SDG 9 also has a high number of occurrences (81), mainly at the initial (47) and development (27) stages, suggesting a continued effort in research and development to strengthen industrial infrastructure. The highest maturity levels (TRL 7–9) are the least represented overall, with only 20 occurrences, reflecting that a significant amount of research work is in the design and development phase, with limited progress towards the deployment phase. These results suggest the need to step up efforts to advance emerging research to higher stages of maturity, especially in areas with low representation.

Fig. 10d, which relates the SDGs to the main pillars of Industry 5.0, shows a significant predominance of actions focused on SDG 11, with a total of 282 occurrences evenly distributed among the three pillars (112 in Sustainability, 82 in Resilience, and 88 in Human-Centricity). This result stresses the importance of building smart cities that are not only sustainable and resilient, but also centered on the needs of their inhabitants. SDG 9 also has a high incidence with 201 occurrences, reflecting a strong focus on sustainable and resilient industrial innovation. Overall, Sustainability is the most frequently addressed pillar (276 occurrences), followed by Resilience and Human-Centricity, both with 206 occurrences. This pattern suggests a strong tendency to integrate sustainable practices into Industry 5.0 strategies, while also highlighting the need for a greater balance and integration of the other pillars.

Fig. 10e illustrates the relationship between the SCOR Model processes and the central digital technologies that support the 4thIR. The Fulfill and Transform processes are the most frequently addressed, with 426 and 294 occurrences, respectively. This indicates the critical importance of these phases in the digital supply chain. Among the technologies, DTs have a strong presence, especially in the Fulfill (81) and Transform (59) processes, reflecting their central role in creating digital replicas to optimize operations. BD and AI are also widely used, especially in fulfillment and transformation, demonstrating a reliance on data analysis and intelligent automation to improve efficiency and decision-making. IoT is predominant in the Fulfill phase (71), highlighting the importance of interconnectivity and real-time monitoring. In contrast, the Order process shows no occurrences, suggesting that technological integration is less focused in this area. Overall, the alluvial graph underlines the need to advance in digital technologies to boost the efficiency and sustainability of supply chains and STs.

Fig. 10f correlates the SCOR Model processes with the levels of technological maturity. The Fulfill process is the most addressed, with a total of 85 occurrences, distributed predominantly at the concept (48) and development (31) levels, indicating a significant focus on refining and developing solutions for this phase of the supply chain. The Transform process is also widely explored, with 62 occurrences, mainly in the concept (40) and development (18) phases, highlighting the importance of innovating in the transformation of materials. Overall, the majority of initiatives are concentrated in the early stages of design (131) and development (74), with a lesser focus on deployment (17), indicating a need to boost technological maturity to reach more advanced stages of implementation. This distribution underscores the importance of ongoing investment in research and development to transform innovative concepts into practical, implementable solutions in the digital supply chain and STs.

Fig. 10 g relates the SCOR Model processes and the main pillars of Industry 5.0. The Fulfill process is once again the most popular, with a total of 210 occurrences, reflecting a significant focus on the efficient and sustainable delivery of products. This process is followed by Transform, with 142 occurrences, highlighting the importance of innovation and material transformation within STs. The Plan process is also well represented, with 91 occurrences, underlining the need for strategic planning in supply chains. Among the pillars of Industry 5.0, Sustainability is the most prevalent, with 218 occurrences, followed by Human-Centricity with 161 occurrences and Resilience with 158 occurrences, indicating that supply chain strategies are strongly focused on sustainable and human-centered practices, as well as being resilient. Future supply systems should not only be efficient and innovative, but also sustainable and humanized, in line with the principles of Industry 5.0.

Fig. 10h correlates the digital technologies promoting the 4thIR with the level of technological maturity. Most initiatives are concentrated in the early stages of conception (350 occurrences) and development (231), with less focus on deployment (55). DTs stand out as the most researched technology, with 129 total occurrences, predominantly in the conception (71) and development (49) stages, indicating a robust and ongoing interest in this area. IoT and BD also show significant numbers, with 106 and 99 hits respectively, reflecting their growing importance in supply chains in STs. In contrast, Robotics and Blockchain have the lowest numbers, suggesting areas with less research and development focus at present.

Fig. 10i relates the digital technologies promoting the 4thIR with the pillars of Industry 5.0. We can see that DTs and IoT are the most prominent, with 308 and 259 occurrences, respectively. These technologies stand out mainly in Sustainability (DT=125; IoT=104) and Resilience (DT=91; IoT=75). AI and BD are also widely represented, with 238 and 233 occurrences respectively, reflecting their relevance in data analysis and intelligent automation to support the three pillars. In contrast, Robotics has the lowest number of occurrences (7), suggesting a lower focus compared to other technologies. Overall, Sustainability is the most addressed pillar (618 occurrences), followed by Resilience (470) and Human-Centricity (467), indicating a strong commitment to integrating sustainability and human-centered practices into Industry 5.0.

Fig. 10j illustrates the relationship between the level of maturity and the pillars of Industry 5.0. The results show that most initiatives are concentrated in the initial stages of design (172 occurrences) and the development (126), with less focus on deployment (23). Sustainability is the most addressed at all levels of maturity, with a total of 130 occurrences. Human-Centricity follows with 97 occurrences, indicating the importance of integrating human-centered approach from the initial design phases through to deployment. Resilience has 94 occurrences, indicating a balanced yet slightly lower focus compared to the other pillars. These results suggest that, while there is a strong drive to explore and develop sustainable, human-centered solutions, there is a need to increase efforts to advance these technologies to the deployment phase, ensuring that innovations can be applied practically and effectively in FSCs and STs.

The next section discusses the findings and points out the main challenges and opportunities for future research.

5. Discussion

The DTs play essential roles in each process of the SCOR model applied to RFSCs, adapting to their particularities and promoting significant improvements. Table 2 summarizes the DTs' main functions and their regional impacts.

In the Planning process, DTs enable the creation of detailed simulations and scenario optimization that increase the accuracy and effectiveness of strategic and operational planning [51–61]. DT solutions with real-time forecasts and predictive analysis can help anticipate demand, plan capacities, and manage inventories more effectively [53,55,60]. In addition, the end-to-end visibility that DTs offers allows for more efficient coordination between the various players in the supply chain, promoting an optimized allocation of resources [180], reducing waste [181], and encouraging more sustainable agricultural practices [182]. Such benefits contribute to better management of regional resources and support the development of local economies with their local products, reducing road traffic and emissions, and improving air quality and the urban environment [183].

In Order management, DTs facilitate real-time monitoring of order status, optimizing management processes, and ensuring on-time deliveries [52,54]. The visibility provided helps to predict potential delays and better coordinate the various players in the supply chain [52–54]. Advanced order management significantly improves customer service while promoting greater connectivity between producers and markets [180,181]. In addition, DTs facilitate access to fresh, high-quality products, encouraging the consumption of regional products [182].

In the Sourcing process, DTs enable the modeling of supplier processes, monitor performance in real-time, and anticipate disruptions, optimizing procurement strategies [51,54,60,61]. Real-time collaboration with suppliers enables proactive information sharing and better coordination in the supply chain [52,56]. DTs are also valuable for risk

Table 2
DTs' roles in RFSCs and their regional impacts (Source: Authors own work).

SCOR Process	DTs Functions	Regional Impacts
Plan	Creation of detailed simulations and optimization of supply chain scenarios, improving the accuracy and effectiveness of planning [51–61] Real-time forecasting and planning [52] Optimization of decision-making [57] End-to-end visibility [53] Predictive analysis [55] Inventory management [60]	Optimizes resource allocation, reduces waste, and promotes sustainable agricultural practices [180] Improves logistical efficiency and reduces operating costs [181] Reduces road traffic and emissions, improving air quality [182] Encourages the use of local products, supporting producers and farmers in the region [183]
Order	Real-time order monitoring and management [52,54] Optimization of order fulfillment processes [52,55] Visibility of order status [52] Coordination between supply chain stakeholders [53] Better customer service [54]	Improves connectivity between producers and markets [180] Facilitates communication and coordination between different regional players [181] Facilitates access to fresh, high-quality products [182] Promotes predictability and stability in demand, benefiting local products [183]
Source	Supplier process modeling [51,60] Performance monitoring and outage forecasting [51,55] Optimization of procurement strategies [54,56,61] Collaboration and real-time shared vision with suppliers [52,56] Risk assessment and mitigation [53]	Promotes the development of regional suppliers [180] Encourages the use of local suppliers [181] Improves the economic resilience of the region [182] Creates jobs and fosters the development of local infrastructures [183]
Transform	Real-time monitoring and control of production processes [51,57] Optimization of manufacturing processes [52,56,61] Increased efficiency and reduced downtime [52,55] Flexibility to respond to market changes [53] Quality assurance [57]	Promotes job creation and the development of local skills [180] Increase the competitiveness of regional industries [181] Reduces distances travelled by conventional vehicles [182] Drives innovation and the modernization of local agricultural practices and industries [183]
Fulfill	Simulation of distribution networks [51] Logistics optimization [52,57,61] Monitoring shipments [51] Forecasting interruptions [56] Product traceability [53] Cold chain logistics management [53] Reducing logistics costs [52,59]	Increase consumer confidence in local products [180] Ensures efficient delivery of fresh, high-quality products [181] Reduces CO_2 emissions and decreases congestion in urban areas [182] Improves regional transportation and logistics infrastructure [183]
Return	Simulation of return processes [51] Forecasting return rates [51] Optimizing the handling of returned goods [52,54–56,61] Reduction of food waste [53] Sustainability [53,54] Efficiency in reverse logistics [56,59] Product recycling and reuse [57]	Promotes environmental sustainability and social responsibility [180] Contributes to regional environmental sustainability [181] Supports the preservation of the region's natural resources [182] Promotes a circular economy [183]

assessment and mitigation, identifying the most cost-effective and reliable suppliers [52,53,61]. By encouraging the use of local suppliers, DTs strengthen local business networks and increase the self-sufficiency of regions [180,181]. This process also fosters job creation and local infrastructure development [182,183].

In Transform, DTs monitor and control production processes in real-time, ensuring greater efficiency, quality, and responsiveness to problems [51,52,57,61]. They optimize production processes by simulating production lines and identifying bottlenecks, which increases efficiency and reduces downtime [52,55,56,61]. Predictive maintenance, made possible by DTs, improves process reliability and allows greater flexibility to respond to market demands [53]. By promoting innovation and modernizing industrial and agricultural practices, DTs help increase regional competitiveness while creating local jobs and regional skills [180,181].

In Fulfill, DTs simulate distribution networks and optimize logistics by monitoring shipments in real-time and anticipating disruptions [51,52,57,61]. They improve logistics and operational management by tracking products, optimizing delivery routes, and ensuring efficient warehouse operations [53,56,57]. Other vital benefits include product traceability and efficient cold chain management [53]. These advances increase consumer confidence in local products and reduce logistics costs and CO^2 emissions, improving urban mobility and quality of life [180–182]. By strengthening regional transport and logistics infrastructure, DTs promote greater territorial cohesion [183].

In reverse logistics (Return), DTs optimize return processes, simulate return flows, and predict return rates, ensuring more efficient management of returned goods [51,52,54–56,61]. DTs can be used to reduce food waste and facilitate the recycling and reuse of products [53,54,56,59]. Efficiency in reverse logistics contributes to preserving natural resources and encourages a circular economy in regions [180–182]. This process promotes environmental and social sustainability while strengthening local and regional waste management practices [183].

DTs have demonstrated significant practical contributions in real-time monitoring, resource optimization, and predictive analysis in RFSCs. For example, Accorsi et al. [58] integrated a DT with life cycle assessment systems to track logistical flows, allowing them to reduce emissions and increase efficiency in transportation and resource use in reusable packaging supply chains. In addition, Maheshwari et al. [54] highlight the ability of DTs to improve production planning and control in real-time, optimizing logistics operations and reducing waiting times and waste through predictive simulations and advanced algorithms.

Although not directly focusing on RFSCs, the studies analyzed demonstrate that the contributions of DTs in regional contexts are widely transferable. Table 3 summarizes the main contributions of DTs observed in regional contexts, grouped by the pillars of Industry 5.0, and explains how these can be applied to RFSCs.

In the Sustainability pillar, DTs stand out for their ability to optimize resource consumption, reduce waste, and promote more responsible practices [64,69,71,76]. In regional contexts, DTs can be used to manage natural resources, such as water and energy, in an integrated and efficient way, practices that can be applied to RFSCs to improve operational efficiency and reduce environmental impacts [95,103,149]. Furthermore, the ability of DTs to reduce carbon emissions by optimizing logistics routes and transport operations is directly applicable to RFSCs, where logistics plays a crucial role [80,104]. The sustainable management of natural resources through DTs, such as soil protection and efficient water use, can also be transferred to RFSCs, strengthening agricultural sustainability [109,149].

Regarding Resilience, DTs offer critical real-time monitoring and event prediction tools widely applied in regional infrastructures [68,92,110]. These capabilities are transferable to RFSCs, where forecasting outages, demand fluctuations, and logistical problems can strengthen the resilience of operations [62,114]. In addition, DTs' adaptive planning and flexibility enable rapid adaptation to changing market or environmental conditions, improving RFSCs' ability to respond to crises [108,113,174]. The resilience of RFSCs can be further strengthened by applying practices observed in regional contexts, such as efficient disaster and emergency management [120,163], which can be adjusted to prevent food losses and ensure continuous supply during crises.

In the Human-Centricity pillar, DTs have significantly improved social welfare in regional contexts, which can be transferred to RFSCs. Food traceability and quality assurance, facilitated by DTs, increase consumer confidence in local and regional products, promoting sustainable consumption [160]. In addition, DTs encourage collaboration between producers, distributors, and consumers, strengthening community networks and promoting social cohesion [79,86]. Community involvement, a central aspect observed in regional contexts, can be adapted to RFSCs, encouraging more inclusive and sustainable production and consumption practices [183]. Although the personalization of services is more evident in urban contexts, adapting to the local needs of RFSCs is a viable way to ensure equitable access to high-quality food.

Table 3
Contributions of DTs applicable to RFSCs (Source: Authors own work).

Industry 5.0 Pillar	DTs' Contributions to RFSCs
Sustainability	Optimization of resource consumption [64,67,69–73,76,80,82,90,98,101,102,104,107,109,110,115–118,120,123,125,135,137,140,141,146,148,151,153,157–160,162,166,169,175–179]
	Implementation of renewable technologies [95]
	Reducing carbon emissions [62,66,71,80,95,98–101,103,104,106,117,126,142,150,156,165,167,174]
	Sustainable management of natural resources [68,69,75,80,88,91,103,105,106,109,113,114,118,119,129,131,139,149,151,155,162–164,167,174]
Resilience	Modeling and simulation for forecasting [68,92,93,120]
	Real-time monitoring with IoT and sensors [62–76,78,80–83,85,88–90,92–100,102–111,113–121,123–127,129–131,133,135–147,149,151,153–167,169–173,175–177,179]
	Strengthening resilience infrastructure [65,67,85,89,92,97,99,101,103,108,125,135,162,163,169]
	Disaster and emergency response [66,98,109,116,142,149,155,159,163–165,167]
	Flexibility and adaptation of systems [108,113,169,174]
Human-Centricity	Promoting social well-being [62–79,81–86,88–97,99–103,105–121,124–133,135–140,142–167,169,171–179,192]
	Improving urban comfort [62–65,67,69,71–75,77,79,80,85,86,90,93,94,98–101,104–106,108,110–113,115,116,119–121,124,127–129,137,140,142–145,149,153,155,159,162,163,167,171,172,174,175,177–179]
	Strengthening public health [68,83,91,96,116,118,130,154,155,170,176,179]
	Improving urban safety [65,68,75,83,102,103,106,107,110,114,117,120,129,132,139,140,148,152–154,161,163,177]
	Citizen engagement and participation [79]
	Offering personalized services [83,88]
	Increased community participation [62,63,65–67,74,76,77,85,86,94,97–99,101,102,104,106–113,115,118–120,125,126,132,133,143,145,146,149,151,153–155,158,159,162,165,167,173]

The SDGs, incorporated into the Sustainability pillar of Industry 5.0, reinforce the role of DTs in modernizing RFSCs. DTs applications promote responsible agricultural practices (SDG 2), reduce waste, and improve traceability (SDG 12) while optimizing critical infrastructures and fostering technological innovation, which aligns with SDG 9. In addition, they contribute to more sustainable cities and communities, strengthening logistics and regional integration (SDG 11). Implementing DTs requires public strategies and investments that consider local specificities and ensure a maximized social, economic, and environmental impact.

Based on our sample analysis, one of the priorities for future research is assessing the impact of DTs in RFSCs. Several publications highlight the crucial need to develop field studies [52,99,115,123,126,174,176,178,181,182] and cost-benefit analyses [52,60,99,110,141,160] to assess economic viability in specific chains, such as fruit and vegetable [53,149,158], while integrating approaches to mitigate risks associated with data privacy and security [54,91,110,129,136,164,168,179] or enabling the simulation of disruptive events to the RFSC [79]. Adoption studies should also advance in parallel, for example, to ensure efficient governance [54,135,151,167], standardization and interoperability [54,91,98,103,120,123,150,152,155,159,163,165–167,175,192], as well as exploring the use of DTs in procurement and predictive support for retailers [54,55].

The technology strand also holds enormous potential. Blockchain, for example [56,75,115], is suggested for mission-critical DT developments, but its use by companies is still in the early stages. Robust backend foundations for DTs will also require innovative user interfaces (UI/UX) to enhance user acceptance within RFSC [62,99,142,154,169,177]. Scalability and inter-regional communications [63] are challenges that need to be considered at a supply chain level of analysis. Moreover, the use cases are exponential in this field, particularly in waste management [69] and the creation of sustainability indices [80], which, combined with improvements in energy consumption [83,91,124] and incorporating social aspects [85,91,105,111,128,173] can make infrastructures more resilient and sustainable [103]. Finally, there is also room for further application of AI (e.g., explainability), ML, and deep learning [127,134,136,147,148,156,162–164,166,170,171,180] and the implementation of scalable query mechanisms [130,144,157,163,172], which makes it possible to optimize both the accuracy of digital models [138] and the integration of DTs with logistics and environmental infrastructures [88,137].

The reflections made by the authors also allowed the identification of research opportunities for the application of DTs in RFSCs. The need to deepen the integration of supply chain processes stands out. While the Transform and Fulfill processes are widely explored, a gap remains in the approach to the Order and Return processes. Research that takes a holistic view of the SCOR model can contribute to a more cohesive and efficient management of logistics flows. The study of DT fleets is essential to allow this level of integration.

Another promising area concerns the synergies that can be obtained with the integration of different technologies. Although current studies emphasize the use of IoT, AI, and Big Data as the backbone of DTs, there is room to explore the integration Blockchain, Robotics, and Cybersecurity. Combining these tools can improve the interoperability of systems and strengthen data security, which are crucial elements for operating DTs in complex environments. For example, it would be interesting to understand the role of human decision trees (DTs) in RFSC.

A roadmap for DTs is necessary during the design and runtime phases of RFSC to mobilize the food industry. However, most studies are at the conceptual or development stages (TRL 1–6). It is imperative to promote research that moves towards empirical validation and practical implementation (TRL 7–9) in real operational contexts. Additionally, it is crucial to examine the trade-offs between the three pillars of Industry 5.0.

Finally, despite the current focus on SDG 9 and SDG 11, there is an opportunity to broaden the alignment of DTs with other SDGs, such as poverty eradication, gender equality, and the preservation of ecosystems. In addition, in-depth analysis of the interrelationships between supply chain processes, enabling technologies, maturity levels, and SDGs could identify the determining factors for successful implementation. The various research opportunities listed offer avenues for new advances in sustainability, efficiency, technological innovation, governance, user interaction, and systematic integration in the development of DTs applied to RFSCs.

6. Conclusions

This SLR investigated how implementing DTs can reconfigure and transform RFSCs, addressing both opportunities and challenges in their modernization and integration. Unlike previous studies, this SLR provides a focused analysis of DT applications in RFSCs, bridging the gap between industrial integration and digital transformation in regional contexts.

The findings demonstrate that DTs can significantly reconfigure RFSCs by enabling real-time monitoring, predictive analytics, and integrated decision-making. These capabilities facilitate the optimization of processes across the supply chain, enhance traceability, reduce waste, and promote resource efficiency, thereby aligning RFSCs with principles of informatization and integration. Moreover, DTs contribute to increased resilience in RFSCs by enabling rapid adaptation to disruptions, such as market fluctuations or supply shortages, thereby fostering sustainability and operational stability.

However, the study highlights critical challenges, including interoperability between systems, managing large-scale data integration, and addressing cybersecurity risks. The barriers can impede the seamless adoption of DTs in RFSCs, especially in regions with limited technological infrastructure or organizational readiness. Nonetheless, the opportunities presented by DTs are substantial, providing tools for innovation, enhanced coordination among stakeholders, and advancing regional supply chain efficiency.

One of the main limitations identified in this SLR is the formulation of the search string, which did not fully align with the specific focus of the study due to the scarcity of articles focusing on the application of DTs in RFSCs. This gap led to a reliance on broader studies of FSCs or regional applications of DTs. Additionally, the review focused on articles from higher-impact scientific databases published within the last five years, which may have excluded relevant contributions from other sources or earlier periods, thereby reducing the scope of the analysis. Furthermore, although SCOR is widely adopted for classifying supply chain processes, other frameworks are also available. Future studies could address these limitations by incorporating additional databases, different languages, and broader time periods, as well as by utilizing empirical analyses that complement the literature with more practical evidence.

Future research directions include the application of DTs in waste management, resource optimization, real-time monitoring of regional supply chains, and promoting sustainable agricultural practices and a circular economy. Integrating emerging technologies, such as AI and blockchain, improves interoperability, data security, and operational efficiency. This research also examines the interaction of DTs with human-centered approaches, promoting inclusion and the engagement of local communities, thereby ensuring that these technologies effectively contribute to sustainable and resilient regional development.

Theoretically, this review contributes by establishing a robust interdisciplinary framework that integrates DTs and RFSCs within industrial informatization. For practitioners, it offers actionable insights into best practices, challenges, and strategies for adopting DTs, emphasizing their role as a critical enabler for achieving efficiency, sustainability, and resilience.

Funding

This work is partially financed through national funds by FCT – Fundação para a Ciência e a Tecnologia, I.P., in the framework of the Project UIDDB/00,326/2025 and UIDP/00,326/2025. The first author is funded by FCT under the Ph.D. grant 2022.09950.BD.

CRediT authorship contribution statement

José Monteiro: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **João Barata:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jii.2025.100851.

Data availability

Data will be made available on request.

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