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Review

Towards the twin transition in the agri-food sector? Framing the current debate on sustainability and digitalisation[★]

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ABSTRACT

A significant weight on the environment is created by the agricultural processes starting from the exploitation of the soil and production to the physical distribution of goods, the retailers' operations and consumption. Agriculture and particularly agri-food is imperative to contribute to solving such global challenges as climate change and food security through cleaner and greener supply chains, where the implementation of smart technologies is one of the major ways to create an impact. The pairing between the potential of digital technologies and sustainability inputs, called twin transition, is currently one of the EU policy's priorities. This research focuses on linking digitalisation and sustainability in the agri-food sector through applications of various digital technologies and the associated contributions to sustainability through the three – environmental, economic, and social - dimensions. To analyse the current debate on sustainability and digitalisation, we have utilised a systematic literature review and qualitative analysis of (policy) documents. The discussion presents a conceptual framework, which follows the process of the integration of a digital technology from its reasoning to the associated sustainability outcomes. The research identifies uneven representation of digital technologies and the structural imbalance of applications towards farming as the agri-food supply chain node and farmers as the major actors' group. The scale of these applications frame the associated contributions to the sustainability dimensions. The analysis of the sustainability outcomes brought by digitalisation through classification of their aspects can advise not only a choice of technology but also managerial and policy directions leading to the transformation. One of the ways to manage twin transition and support competitiveness on both firm and sector levels is development of a strategy, which can be supported by policy making.

1. Introduction

Food systems contributed decisively to the current climate crisis, their organisation and functioning created the paradoxical situation of unequal access to nutritious diets despite an overabundant production of food (FAO, 2023). Many experts, policymakers, and activists voiced their concerns and called for a profound change of food systems to achieve sustainability and guarantee equitable access to food (Willett et al., 2019; Annosi et al., 2023).

The deployment of smart and digital technologies is currently seen as a promising avenue to solve these crises (Guthman and Butler, 2023; Klerkx and Villalobos, 2024). Smart agriculture and industry 4.0 technologies could help firms and value chains to develop cleaner and greener production processes, while increasing efficiency and productivity. Their contribution in making data available from the field to the table and back, enabling optimal decision making along the value system, is seen as a relevant contribution towards the green transition (Rotz et al., 2019a, b; Senturk et al., 2023; Farm to Fork strategy, 2020; Costa et al., 2023).

Digital technologies lead to economic effects only if associated with

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changes in business models and institutions (Auzan, 2019). Moreover, the digital economy does not provide an overall decrease in transactional costs. While digital innovations lead to decrease of some transactional costs, such as costs of management and control due to higher transparency and trust, it has increased costs of other types, for example, of data protection and property rights (Auzan, 2019; Tambovtsev, 2014). Therefore, a choice for a digitalisation should be a weighted and evaluated decision of actors within the supply chain in particular and institutions in the sector in general.

Digital transformation, which is understood as 'the integration of digital technologies by companies and the impact of the technologies on society', is one of the EU's priorities (EU Monitor, 2022). The newest trends in EU policy making aim at coupling digital technologies with sustainable development into the so-called twin transition, or 'twinning the green and digital transitions in the new geopolitical context' (European Commission, 2022 Strategic Foresight Report; Muench et al., 2022). A development of a digital strategy is one of the ways to manage an appropriate digital transition in the agriculture sector towards its deep and comprehensive transformation. Moreover, the development of a suitable strategy based on both firm's characteristics and objectives on the one side and technological capacities on the other side can contribute to overcoming the existing challenges in digitalisation. As a policy's priority, which attracts various investments and resources on different levels, twin transition requires a strategic approach to manage technological deployment according to nodes and actors within the supply chain. Moreover, the scope and efficiency of these deployments will frame (stimulate or limit) the expansion of the sector's sustainability and achievement of goals of sustainable development.

Most of the existing academic and policy debate on digitalisation and sustainability in the agri-food sector and agriculture focuses on the role of digital technologies in expanding sustainability and sustainable development. It highlights the advantages, both potential and actual, brought by the implementation of various digital technologies, as well as discusses the challenges and barriers to technological adoption. Nevertheless, there is a lack of attention to the main problems behind selecting a specific digital solution. Moreover, the sustainability outputs brought by different technologies according to their specific implementation process within a supply chain require a more detailed investigation.

Specifically, while advocating for the widespread adoption of digital technologies, policy-makers should not consider the digital transition as a clean slate, but rather take stock of the extant body of knowledge developed in various streams of literature in diverse disciplines. Our study aims at contributing to this effective match between policy-making and the advancements of research in digital technologies and transition. Our review, in particular, aims at developing a more detailed overview of digital transformation of the agricultural and agri-food sector. It addresses digital technologies' characteristics, applications in relation to the supply chain's nodes and identification of engaged actors. Moreover, it focuses on sustainability outputs or outcomes, which are related to the specificity of the digital transformation process. In such a way, to understand the sustainability outputs brought by the application of digital technologies within agri-food supply chains, this research aims at unpacking the complex process of digital transformation within the sector. In so doing, we hope to support policy-making in avoiding misallocated enthusiasms and at the same time being aware of the areas that deserve attention with more urgency.

Our research was driven by these main research questions.

RQ1: What are the reasons behind digitalisation and implementation of specific digital technologies to increase sustainability in the agricultural and agri-food supply chains?

RQ2: Which agri-food supply chain's nodes and actors are engaged in digital transformation?

RQ3: Which sustainability outcomes do these digital technologies bring?

The paper thus presents the results of a systematic literature review and document analysis aimed at providing managers and policy-makers with a granular understanding of the inputs and outputs of digital technologies at different stages of agricultural supply chains, as well as of the critical factors determining their adoption or lack thereof.

The paper is composed of introduction, policy background and followed by theoretical framework, which comprises sustainability pillars framework and a strategic approach to digital transformation. The methods section is followed by discussion, which is built up by three main subsections: unpacking digital technological advancement within the agri-food supply chain, linking it to sustainability dimensions, and the role of a strategic approach in undertaking digital transformation in the agri-food. The discussion closes with future research agenda and is followed by conclusion.

2. Policy background: the European agri-food towards twin transition

One of the largest recent policy initiatives on the EU level to promote and deliver climate-neutral goals within sustainable development is the European Green Deal. A set of policy initiatives by the European Commission was authorised in 2020 (European Commission, 2020) and focused on the reduction of greenhouse gas emissions in all economic sectors. The EU Green deal consists of several policy initiatives, including launching in 2020 the From Farm to Fork (F2F) strategy in the farming sector, which aims at fair, healthy and environmentally friendly food systems. It is the first initiative of that scale at the European level which focuses overwhelmingly on food systems. The timeline of the strategy's actions started in 2022; it focuses on the three sectors: empowering citizens to make healthy and sustainable choices; supporting farmers and fishers and enabling the transition; and protecting nature and climate. The F2F strategy primarily aims not at concrete decisions but 'rather communicates the values, objectives and instruments that will govern European food policy in the future' (Reinhardt, 2022, p. 3). Among its benefits, the development of 'an institutional alignment in the innovation system by providing a clear agenda for transformation and proposing various innovation support measures' can be named (Reinhardt, 2022, p. 2). At the same time, an advanced or complete institutional alignment requires a clear vision on engaged institutions and their functions within a particular policymaking.

The shortcomings of the strategy concerns its inability to encompass 'key links in and between food systems' (Mowlds, 2020) and to address the central role of education and training to support the required transition (Moschitz et al., 2021, p. 34). The first argument refers to the value chain, and in particular to the continuity and interconnectedness of specific nodes that are the basis of coordination and effective performance. A second topic is the importance of education and training in enriching actors' competencies, first of all farmers', to implement the novel technologies. Moreover, new competencies and knowledge are aimed not simply at managing the technological implementation but also to its acceptance and subsequent integration in labour processes. An application of digital technology is a complex process which involves its adoption by actors involved in its use and is often rooted in their cultural norms and traditions.

In such a way, in the last policy initiatives the institutional actors have at last come to the necessity of interconnecting sustainability on the one hand and digitalisation on the other in the agri-food. Although, the ambiguity of the sustainability concept developed in both academic and policy debates tend often to complicate its application.

To overcome this challenge, our research appropriates the triple bottom line framework in order to analyse the variety of sustainability aspects with the interconnections and interdependencies among them. In such a way, this utilises the potential of a holistic and integrated understanding of such a complex and multi-layered phenomenon as sustainability.

3. Theoretical background

3.1. The three sustainability pillars framework

While the urgency of addressing the sustainability issues is out of the question, the practical side of improving sustainability can be perceived as a challenge by both policy makers and managers in the agricultural sector. The ambiguity of the concept is translated in both policy documents and research outputs, which, in turn, obstacles the development of a coherent and comprehensive approach to address the global challenges.

Although it is difficult to find the very first introduction of sustainability into official policy and academic debates, often the concept's origin is associated with the United Nations Brundtland Commission or the World Commission on Environment and Development (WCED). In the commission's report 'Our Common Future' (1987) sustainability was defined 'as development that meets the needs of the present generation without compromising the ability of future generations to meet their needs' (Thomsen, 2013). To ensure that the current needs are not negatively affecting the needs of future generations, the framework of Sustainable Development Goals (SDGs) was developed to improve the current and future living conditions. One of the widespread approaches to conceptualise the variety of those goals, presented in both academic research and in the policy sphere, is the triple bottom line framework, which is based on the three pillars of sustainability - environment, economy, and society, or planet, profit and people. Therefore, this framework encompasses three dimensions of sustainability - environmental, economic and social, which are interconnected and create the basis for sustainable communities and industries.

The economic understanding of sustainability is often associated with economic growth and an increase in efficiency, which presupposes that resources are allocated to their highest valued use and, consequently, there is a rise in productivity and capital assets (Elliott, 2005). Then, environmental, or ecological, sustainability in agriculture focuses on the continued productivity and functioning of ecosystems, which includes a range of factors from resource base quality, the preservation of physical conditions and resources and of biological diversity to productive capacities and climate change mitigation (Yunlong and Smit, 1995).

Social sustainability can be defined through the human appropriation of the environment and focuses on the availability of access to social resources by current and future generations, represented in intra- and inter-generational equity respectively (De Gennaro and Nardone, 2014, p. 25). Social, or societal, aspects of sustainability are largely based on broad stakeholder input and include, but are not limited to, animal welfare, values and responsibilities of consumers (as citizens), (un) documented labour conditions and issues, public engagement and others (von Keyserlingk et al., 2013). A review of the literature on the social pillar of sustainable development by Murphy (2012) resulted in a conceptual framework, which is based on the concepts and policy objectives outlined in the research, which identifies four comprehensive social concepts: public awareness, equity, participation, and social cohesion.

Overall, the need to address sustainability issues throughout all industries and economic activities, and agriculture and agri-food in particular, is the agenda of the governments, policy makers, managers and academic community. The rhetoric might differ from policy to academic points of view, whereas all parties share the standing point on the crucial role of smart and digital technologies in the sustainability agenda. In this context, our research aims at linking the perspective of policies to academic debates on these topics.

3.2. Digital transformation levels: a strategic approach

The reproduction of the established operations, relations, and transactions among different actors within nodes of an agri-food supply chain ensures its stability and durability. The chain's stability includes not only repetition of certain operations and transactions within established networks of actors and stakeholders but also involves certain economic, environmental, and social effects. Although, to achieve a pervasive transformation in agri-food, which will lead to a turning point in fighting the global sustainability challenges, the existing efforts have shown their insufficiency. To enhance the sustainability of agri-food supply chains, digitalisation may provide a vast range of solutions (e.g., Checchinato et al., 2023).

Integration of innovative technologies lead to disruption of the established order of operations and networks of involved actors by providing with the new order and its logic. The disruption stage is not the final destination for the adopted changes, it is a process which leads to the new order. In turn, the new order is a set of operations, rules and networks, which has to be established through the reproduction by the actors. In such a way, policies and business activities ought to motivate the actors and institutions to reproduce the novel technological order based on digital solutions. However, digitalisation, or the process of application of digital technologies, is not digital transformation yet, both in theory and in practice. As Gong and Ribiere (2021) underline, 'defining digital transformation as a fundamental change is significant since it allows for differentiation from other non-fundamental changes, such as digitization and digitalisation'.

One of the ways to achieve transformation and replace the traditional order by a new one is an integration of various strategies. A strategic approach allows to correct the goals to expand sustainability. Inclusion of digital technologies in operations and interactions is addressed by digital strategy. In turn, a strategy which focuses on establishing novel organizational and operational set-ups based on digital solutions, is a strategy of digital transformation.

The strategic approach takes into account the changing functions of economic activities (in particular, nodes in supply chains) and the expanding diversity of actors and stakeholders. It is aimed at their alignment at different levels to ensure achieving the set goals, such as sustainable development. The coupling of digitalisation and sustainability, which lies at the heart of twin transition, requires not simply change in functions and inclusion of novel actors, but also increased coordination of all system's levels.

The process of integration of digital and smart innovations in the sectoral operations and transactions is a complex mission which affects companies and goes beyond their borders (Matt et al., 2015, p. 339). The complexity of the process requires a structured and planned approach, such as a strategy, 'the creation of a unique and valuable position, involving a different set of activities' (Porter, 1996). The leveraging of digital resources aims at the creation of a differential value. Digital strategy can be approached as a functional level strategy, which is 'aligned but essentially subordinate to business strategy' (Bharadwaj et al., 2013, p. 472; Matt et al., 2015) follow the 'alignment' approach, which requires digital or digital transformation strategy in order to 'account for their company-spanning characteristics, to cut across other business strategies and should be aligned with them' (p. 339). The alignment refers to the necessity of interconnecting and coordinating the existing and future strategies, so that they represent the company's vision and target similar goals.

Generally speaking, digital strategy focuses on the development and management of digital infrastructure within a company (or sector, depending on the scope). It aims at adjusting or developing the infrastructure according to the company's structural and functional characteristics in a way to achieve the anticipated goals. The implementation of a digital strategy does not necessarily lead to digital transformation within a firm or sector. Moreover, as Chamorro-Premuzic (2021) stated, 'even the best technology will go to waste if you don't have the right processes, culture, or talent in place to take advantage of it'. In this way, the access to digitalisation and certain technologies does not guarantee its successful implementation and motivation to reproduce its usage.

Digital strategy differs from digital transformation strategy. While the former focuses on digital infrastructure and its management, the latter one embraces transformation of products, processes, and organisational aspects due to the exploitation of novel technologies. Digital transformation strategy can be understood as the key link between digital (business) strategy, on the one hand, and digital transformation, on the other hand (Brown and Brown, 2019). A strategic approach aims at managing not simply the implementation of technologies but also at understanding the directions of change of both the organisation and the sector. Digital transformation can be defined as 'the cultural, organisational and operational change of an organisation, industry or ecosystem through a smart integration of digital technologies, processes and competencies across all levels and functions in a staged and strategic way' (i-SCOOP, 2018). It is not limited to the integration of both digital technologies and information and communication technologies into manufacturing and production but also 'includes aligning with partners to access external knowledge' (Schuh et al., 2017). Overall, digital transformation is a complex process that 'aims to improve an entity by triggering significant changes to its properties through combinations of information, computing, communication, and connectivity technologies' (Vial, 2019, p. 121).

Digital transformation is a complex phenomenon, which involves all components of a sector and all the processes and areas of a firm. It is based on the changes brought about by digital technologies. Digital transformation strategies, in turn, 'seek to coordinate and prioritise the many independent threads of digital transformation' and encompass four essential dimensions: the use of technologies, changes in value creation, structural changes, and financial aspects (Matt et al., 2015, p. 339). In contrast, the essential components of digital transformation include such as people, data, insights, and action (Chamorro-Premuzic, 2021). Overall, digital transformation as a complex phenomenon encompasses various dimensions and requires adequate management. Similarly in the agricultural sector, strategies are developed to address the existing and potential risks and to manage the transformation. In doing so, strategy is grounded on the set of clear and sharp goals and challenges. Eventually, the transformation involves not simply the implementation of new technologies but moreover 'the changes in thought, organisational behaviour, and culture' (Senturk et al., 2023, p. 6).

In such a way, digital transformation involves changes and offsets at different levels, from micro level of single (agri)firms to macro level of the national (agricultural) sector. The effectiveness of the transformation, which involves sustainability outcomes, depends largely on how alignment and coordination of diverse activities and actors is managed at those levels, either a firm's or a sector's strategy.

Our literature review aims at analysing previous research findings with this focus: from the analysis of the digital technologies adopted, throughout the role of nodes and actors involved in the supply chain, to finally identifying the most common outputs (Fig. 1). This will help us to answer our research questions.

4. Methods

To investigate the outlined research questions and the general aim of this research, the methods combined systematic literature review (SLR) and qualitative analysis of documents. Within this research strategy, both methods utilise the principles of qualitative (document) analysis. In particular, the methods are guided by the principles of thematic analysis, whose main study subjects are themes. In our research, themes are considered within their context (i.e. application of context) to improve the relevance of the extracted data and its further conceptualisation. At the same time, the themes are tied not only to the context but also to the phenomenon itself to avoid a common error during the analysis (Mishra and Day, 2022, p. 190). The main themes are illustrated on the basis of literature review or theoretical background, as well as they 'largely emerge during data analysis' (Ibid., p. 188). In our research, themes are rooted in theoretical background (and tied to the phenomenon), as well as in the policy background (and tied to the context).

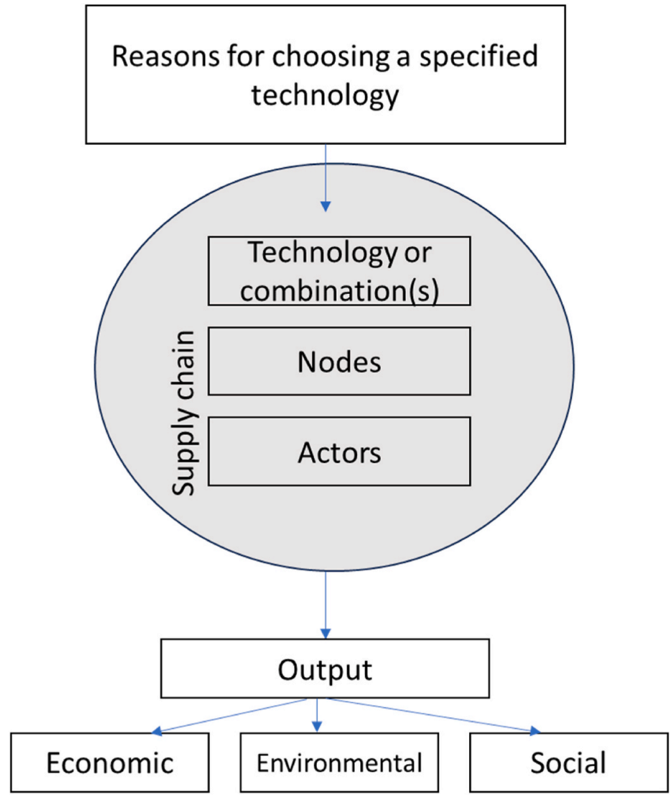

Fig. 1. Conceptual framework.

The SLR follows the PRISMA protocol (Moher et al., 2015), a protocol adopted in many studies related to sustainability as well as to the agri-food sector (e.g., Tragnone et al., 2022), because it (Fig. 2) ensures a high level of transparency and reduced distortion. Screening and eligibility of papers were performed by two researchers to avoid subjective bias. In the screening phase we considered only abstract. 121 records not related to the agri-food sector were excluded. Then, we searched for the full text: 15 papers were excluded because they were not available, 2

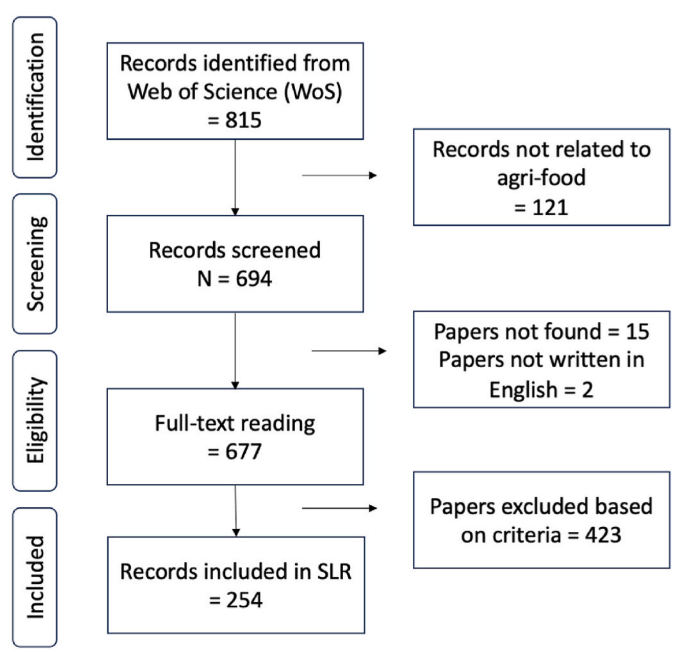

Fig. 2. The SRL protocol.

items were excluded because they were not written in English. Then we read the full text papers and excluded 423 records because they did not meet the inclusion criteria (see Table 1). In such a way, the final dataset for the analysis consisted of 254 papers (see Table 2).

Web of Science (WoS) was selected as the main database to investigate the relevant literature. We identified keywords based on our theoretical background to achieve a representative sample of papers that investigate both the digitalisation and the sustainability topics in the agrifood sector. The final search was performed on November 6, 2023. We used the following key search: (agri* OR agri-food OR agrifood OR food OR agribusiness OR agri-business) AND (industry 4 OR smart OR smart-agri* OR agri-tech OR agritech) AND (sustainab*). The search was limited by the topic parameter (title, abstract and keywords). Moreover, we analysed only the articles under the WOS social-science index (including management) as shown in Table 1.

The thematic analysis allows us to identify common patterns emerging from the data (Mishra and Day, 2022, p. 187). The main themes were developed on the basis of theoretical background, in particular the sustainability pillars approach and the strategic approach. Each theme was categorised into several more specific codes. While themes were mostly developed on the basis of the utilised theory, codes emerged during data analysis. The coding process had three levels: open coding was followed by focused second-order codes that were aggregated into theoretical codes, allowing us to revisit our themes on the basis of the codes.

The text analysis and themes' identification were based on several key techniques (Ryan and Bernard, 2003). Firstly and foremost, we have employed the technique of repetitions, which is one of the most common ones in theme analysis. Repetitions can be perceived as 'topics that occur and reoccur' and 'recurring regularities' (Ibid., p. 89). This technique overlapped with theory-related material based on prior theorising (Ibid). Then, to develop certain sub-themes and codes, we used the technique of similarities and differences. It is based on systematic comparisons across data units and pairs or groups of expressions. It was especially useful to identify data for different pillars of sustainability, which have similarities due to pillars' interconnections (for example, food safety as a social pillar and food certification as an environmental one).

Three main themes were identified: reasons to opt for a digital solution; its application process within the supply chain; sustainability pillars. The first theme of digitalisation motives included such codes as economic, environmental, and social reasons. Then, we have codified technologies mentioned in the papers. We have grouped certain technologies based on relevant reviews. In terms of digital application within the supply chain, we coded the node of the supply chain or phase of the extended production and activity system at which a technology is implemented (the phase in the value chain). Also we identified actors involved in or affected by these digital technological implementations. The third theme of sustainability was categorised into sustainability outcomes according to the three pillars approach. These outputs or outcomes were classified according to each sustainability pillar, considering the interlinks among these dimensions.

Table 2
Top Publication outlets.

Journal	Number of papers
SUSTAINABILITY	90
IEEE TRANSACTIONS ON ENGINEERING MANAGEMENT	7
LAND USE POLICY	7
JOURNAL OF CLEANER PRODUCTION	6
BUSINESS STRATEGY AND THE ENVIRONMENT	5
LAND	5
NJAS-WAGENINGEN JOURNAL OF LIFE SCIENCES	5
SCIENCE OF THE TOTAL ENVIRONMENT	5
SUSTAINABLE PRODUCTION AND CONSUMPTION	5
TECHNOLOGICAL FORECASTING AND SOCIAL CHANGE	5
INTERNATIONAL JOURNAL OF ENVIRONMENTAL RESEARCH AND PUBLIC HEALTH	4
JOURNAL OF ENTERPRISE INFORMATION MANAGEMENT	4
TECHNOLOGY IN SOCIETY	4

The example of the process of theme building is the following: firstly, the theme is sustainability pillar. Its sub-theme is an economic sustainability pillar, the defining aspect. The open codes at the first level are 'access to new markets', 'development/integration of new business model', 'data-driven business model', 'access to new suppliers/consumers', 'new labour patterns and shifts', 'creating new jobs', 'new digital marketing strategy' and else. The second level code or category is 'novel economic opportunities/widening of horizon of opportunities'. Thus, the economic pillar of sustainability is conceptualised through various aspects, and one of them is new economic and business opportunities.

Alongside the systematic review we performed a qualitative analysis of documents. Within this strategy, we perceive qualitative analysis of documents as equal to the document analysis, and their main principles as similar. Document analysis 'involves skimming (superficial examination), reading (thorough examination), and interpretation'; and this process 'combines elements of content analysis and thematic analysis' (Bowen, 2009, p. 32).

The target documents are official policy documents and reports, which address a certain policy and its initiatives - the European Green Deal. Documents and reports were extracted from the official websites of the European Commission and European Council, as well as the Joint Research Centre (JRC) as the European Commission,'s science and knowledge service. The main criteria to include documents in the dataset was, firstly, presentation or discussion of certain policy initiatives or implementations within the EU agriculture and agri-food sector. Secondly, the document had to address digital-related aspects: digitalisation in general or application of certain technologies. The third

Table 1
Literature identification, screening and eligibility criteria.

Literature identification	Database: Web of Science Publications time period: 2012–2023 Keywords: (agri* OR agri-food OR agrifood OR food OR agribusiness OR agri-business) AND (industry 4 OR smart OR smart-agri* OR agri-tech OR agritech) AND (sustainab*) In: Title, abstract, keywords Inclusion criteria: Social Science, including Management
Literature screening (abstract reading)	Inclusion criteria: Related to the agri-food sector
Literature eligibility (full text reading)	Exclusion criteria: 1. Papers not found 2. Papers not written in English
Paper included in the SLR	Exclusion criteria: 1. Papers related to digitalisation only, with no relation to sustainability; 2. Papers related to sustainability without digital technologies involved or mentioned; 3. Papers about climate smart agriculture without the employment of digital technologies

criteria was mentioning sustainability or/and sustainable development. We identified 35 documents. The documents were analysed according to the same principles of thematic analysis as papers for SRL.

Conducting the document analysis along with SLR brings insights into possible differences and even gaps in policy making discourse, on the one hand, and academic debate, on the other hand. The main objective of both discourses under analysis is the presentation and approach to linking digital transformation and sustainability challenges through its conceptualisation as 'twin transition'. The investigation of this gap can inform policy making regarding twin transition, digitalisation and sustainable development of agriculture, as well as help in evaluating possible measures to address these challenges.

The research methods are perceived beneficial due to their usage of academic literature and policy documents to bridge the representation of the agri-food's twin transformation in both academic and policy discourses. However, the research limitations are related to, firstly, the degree of coherence between the methods (i.e. geographical scope). While the focus of policy review is on the European level, the academic dataset covers countries worldwide. Secondly, while the policy documents focus on certain European agricultural policies, SRL's articles also considered other policies. Nevertheless, the combination of two analytical methods provides deeper investigation in interlinking digitalisation with sustainable development and conceptualising them into the concept of twin transition. Moreover, it highlights challenges arising in the process of policy implementation. Last but not least, the research faces the 'traditional' challenge of generalisation of qualitative research (Fischer et al., 2007).

The descriptive analysis focuses on evolution, geographical distribution and top productive journals. The academic papers have been published between 2012 and 2023. The popularity of the topics has been slowly increasing year after year since 2017 with the peak in 2021–2022 (with 69 and 65 papers respectively). In this way, more than 70% of the selected papers have been published in the last three years (Fig. 3). The parameters of the dataset of policy documents are defined by the thematic focus of the qualitative analysis of documents. Since the analysis has mostly focused on the novel European Green Deal policy, all the documents were published between 2020 and 2023 after the policy's approval in 2020. This element might partly explain the increasing interest by researchers as well.

The analysed papers were published in 103 different publication outlets, which illustrates a diffusion across different sources. However the dominant source is the *Sustainability* journal, followed by *Land Use Policy*, *IEEE Transactions on Engineering Management* and *Journal of*

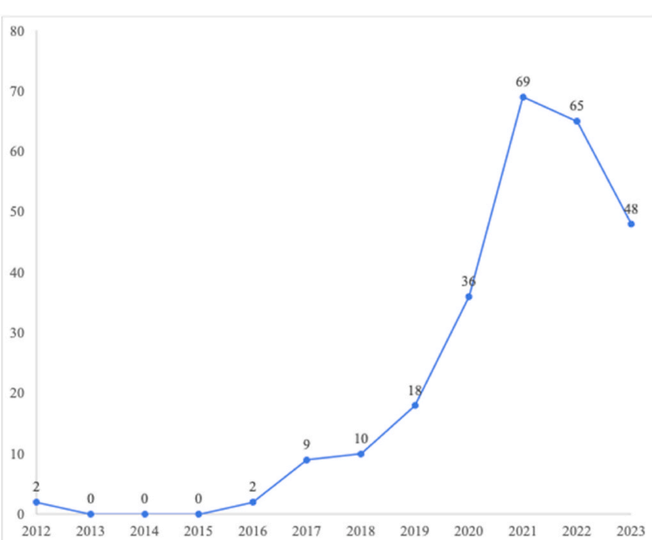

Fig. 3. Number of studies published per year.

Cleaner Production. All top outlets are transdisciplinary.

Table 3
Geographical scope of SLR papers.

Region	Amount	Percentage
Asia	48	19%
Europe	46	18%
Australia and New Zealand	9	4%
Africa	8	3%
Northern America	7	3%
Middle East	7	3%
Latin America	3	1%
Multiple	12	5%
No region	113	45%

In terms of the geographical scope (Table 3), most of the papers are focused on the Asian and European areas (with 48 and 46 records respectively): The most analysed countries were Asian ones, including China and India, and European ones (mainly Italy and Germany). The category of 'No region' groups review papers or papers without specified geographical focus; whilst 5% of the papers studied multiple areas/ countries.

Although the analysed topics have been gaining unprecedented attention in the last few years, they are rooted in the previous research about digitalisation and, especially, sustainability in the agricultural and agri-food sector. While both topics have been largely investigated in policy and academic discourse, the focus on interlinking both phenomena, which can be conceptualised as 'twin transition', is a fairly new agenda to investigate further.

5. Discussion

Our analysis focuses on the investigation of digital technological applications within the agri-food supply chain, and on how they are pursued and framed by the policy making on the European level. The inquiry begins with the identification of reasons for applications and choices of certain technologies (RQ1). In order to analyse how digital technologies are implemented within the agri-food supply chain (RQ2), we combine a functional approach to the supply chain through the analysis of its nodes with a multi-actor approach. Since one of the strongest motives behind the choice for digital solutions has been its promise to bring sustainability outcomes, according to both academic research and policymaking, we focus on interlinking digitalisation with sustainability. To examine how digital and smart technologies transform and expand agri-food's sustainability (RQ3), the smart technological adoptions are analysed through environmental, economic, and social dimensions, and their interlinks. Such an analysis provides a complex approach to the changes of the sector's operations and interactions brought by digitalisation. Fig. 4 visualises the conceptual framework by showing how the research questions illustrated are concatenated and present the main findings, which are discussed later in this section. It follows the process of the integration of a digital technology from its reasoning to the associated sustainability outcomes. The identified outputs, which are one of the main research findings, conceptualise how the novel technological achievements contribute to sustainability.

5.1. Digitalisation in agri-food: unpacking the digital technological advancement

The process of implementing a digital technology or solution in the agri-food supply chain is a compound task, which involves a multiplex of actors, factors and chain's elements. Prior to the actual application, the need to choose a digital solution should be grounded or validated not only on the basis of the advantages brought by a specific digital solution to address a problem or task, but also of the incorporation of the firm's objectives and characteristics. Our research focuses, first of all, on identifying reasons behind the initial decision to implement a digital

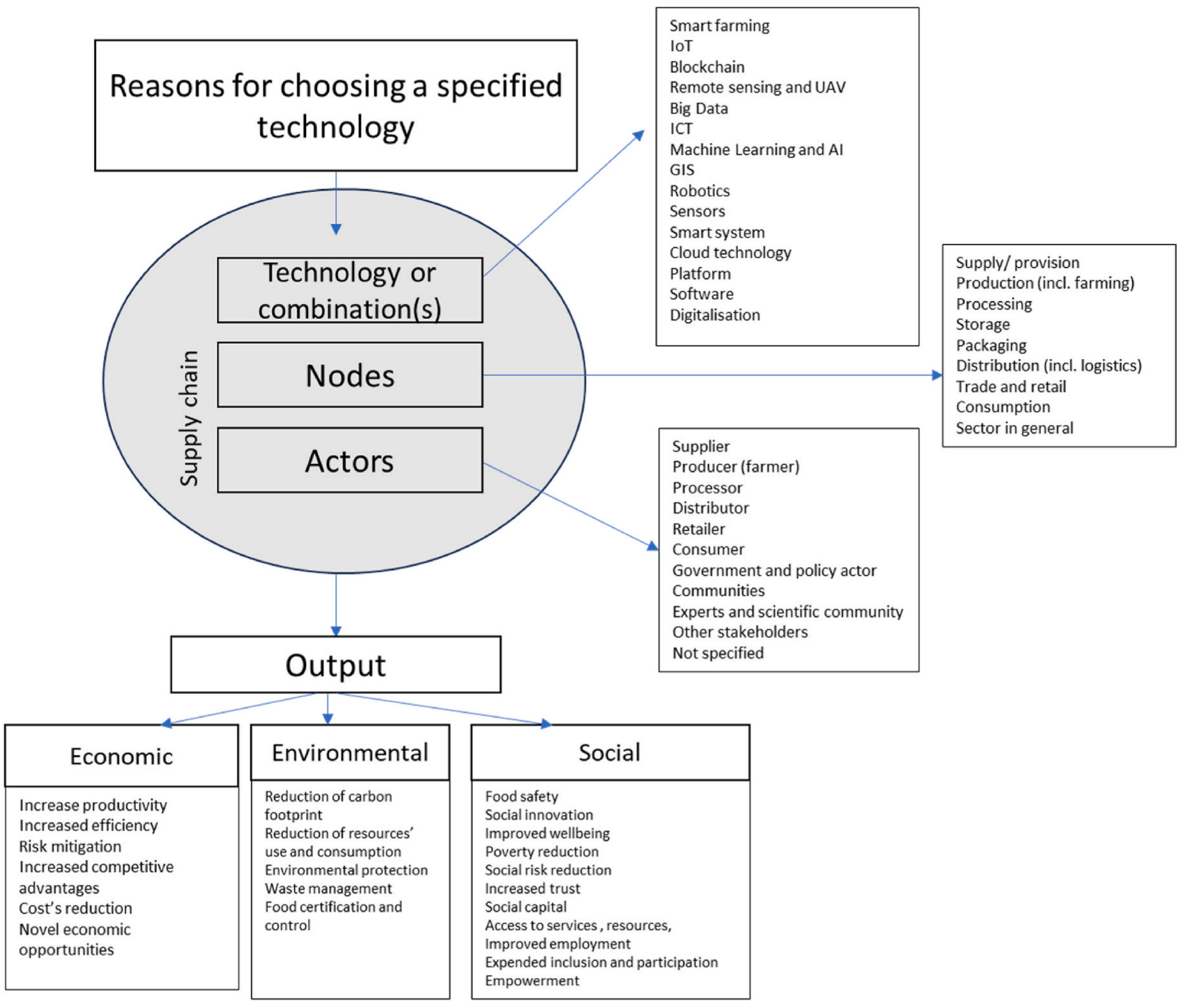

Fig. 4. The conceptual framework with the main findings.

solution instead of or alongside other innovations. Then, a decision to choose a certain digital technology requires reasoning as well, which is based not simply on technological characteristics but also firm's capacities and goals.

5.1.1. *What are the reasons behind digitalisation?*

The extant research focus on the role of reasoning for digitalisation is rooted in the strategic approach. Collins dictionary, for example, defines reasoning as 'the process of forming conclusions, judgments, or inferences from facts or premises'. The process of reasoning lies at the heart of goals and objectives setting, which is one of the key elements of a strategy. The goals should align with the firm's features, market's or sector's configuration and its current state, and global and local challenges to develop a plan of key initiatives.

The understanding of reasons behind embarking on the digital path is crucial to identify the final technological outputs. Later, these outputs have to be compared with the original set goals, in particular to analyse the level of its completeness and the efficiency of conducted activities and measures.

Our analytical approach based on the theoretical framework of sustainability allows us to group the reasons behind digitalisation according to the three sustainability pillars (social, economic, and environmental/ecological). This analytical approach departs from the idea of twin transition meant as the coupling of digital innovations and green development. The environmental reasons are the most articulated in the dataset: they are presented in 181 papers (71,3 % of the dataset) and all analysed policy documents. These reasons include mostly the need to reduce the industry's ecological footprint, mitigation of greenhouse gas emissions, and the reduction of agricultural inputs (fertilisers, pesticides, irrigation water, and others). Another significant challenge to address with digitalisation is the growing amount of waste, in particular food waste, which has both ecological and economic aspects. The discussion of environmental motives in the academic papers is mostly presented in reference to the existing policies, institutions, and policy concepts, sustainable development and SGDs in particular, a number of which are presented in the analysed policy documents. This might be an argument for a deep connection between policy context and justification for digitalisation.

Economic motives are less covered by academic papers (164 papers, 65 %) and policy documents (29 documents, 83 %). The main economic challenges are related to the disproportions in the allocation of resources. Then, there are high barriers and costs to access market(s), which are often too high for small businesses: information related costs and imbalances hinder market access for smallholder farmers (Deichmann et al., 2016), as well as market pricing information (Wyche and Steinfield, 2016). Mehmood et al. (2021) addresses the role of logistical and infrastructure challenges, such as issues related to reverse logistics. In broad terms, the central economic challenge is the necessity to increase productivity and efficiency of the sector, which are low partly due to its current technological state.

Social motives are the least articulated in the academic literature (111 papers, 47 %), while discussed at length in policy documents (89%). The central social challenges to address are increasing food insecurity and need for food safety, which can be targeted by technologies in various ways: policy documentation stresses the latter motive. Other issues are related to labour conditions, such as labour time and heavy, often dangerous, work (Balafoutis et al., 2020). In this area, the role of innovation and digitalisation appears relevant: labour time is often connected to time-consuming usage of old or outdated tools, engines, and know-how (Mor et al., 2021), which requires novel innovations. Also, a high level of work injuries and accidents require novel methods to address work routine (Scott et al., 2017). The official documents' discourse also refers to problems related to education, especially in rural communities, but does not directly connect them to digital technologies (F2F Strategy, 2020).

However, the overwhelming majority of both papers and policy documents refer to two main reasons for digitalisation - climate change and food insecurity. While the use of digital technologies to reduce environmental impacts and decrease food production have been widely articulated, the selected papers do not provide in-depth reasons regarding the choice of specific technologies. One of the central challenges for the research was a separation of reasons to undertake a digital solution, on the one hand, and its obtained or expected outcomes, on the other hand. In most of the academic and documents dataset, reasons were not explicitly given and were overlapped with technology's effects on transactions and operations. However, this separation is crucial for the problem identification and goal setting, which will define digital solutions. It is also essential for planning and strategy development, as well as for the evaluation of digital implementations since a lack of reasoning and justification of a digital solution can result in socio-economic and ecological losses and transaction costs. A clear understanding of challenges and related goal setting is necessary for policy making, as well as for individual agribusinesses.

5.1.2. Which digital technology to implement?

Digitalisation as a process requires to integrate digital technologies in various operations and interactions and it does presuppose the use of specific material and immaterial artifacts (hardware and software). The choice of a certain technology should be based on its characteristics and also the firm's capabilities. Moreover, within a strategic approach a technology is chosen on the basis of these parameters, as well as set goals and objectives. Therefore, the reasoning also at this stage is important to assist the choice of the most appropriate and efficient digital solution (can include one innovation or combination of several ones).

When the smart solution has been reasoned and chosen, its deployment within a supply chain requires to focus on its elements or nodes. We have allocated particular technologies (and their groups) with the application in a supply chain node and engaged actors. In our analysis, we have identified several major technologies, which are sufficiently presented in the dataset in terms of their technical characteristics and operation. Some of the technologies were arranged in a technological group with similar characteristics, for example smart systems and smart farming. The analysis includes 14 technologies and groups, plus a general Digitalisation group (63 papers). This latter group refers to the application of multiple technologies within precision agriculture and Agri-food 4.0 concepts and often without a detailed coverage of specific technologies. In general, our classification (Fig. 5) has been informed by the scoping review by Green et al. (2021), as well as types of smart technologies in policy documents.

Smart or precision farming is a group of technologies providing support to decision making based on digital technologies, including big data, the cloud, and Internet of Things (IoT), at the farming stage of the agri-food supply chain (discussed in 40 papers). This technological group is based on technologies, which are also analysed individually in other papers, but within smart farming their combination is key for operation and management. Moreover, it focuses on the technological advancement of a specific supply chain's node - farming or production.

The most covered technology is Internet of Things (78 papers), which 'aims to unify everything in our world under a common infrastructure, giving us not only control of things around us, but also keeping us informed of the state of the things' (Madakam et al., 2015). Moreover, IoT received the widest attention and expectations to transform agri-food not only in academic research, but also policy documents (in particular, in the F2F strategy's documents). Going down in the ranking, blockchain (48 mentions) 'enables secure, reliable, and efficient distributed management systems without a trusted third party, which is a core part of centralised supply chain management' (Joo et al., 2021). This technology ensures traceability within the whole network and allows to track every single operation and transaction. It is used to track down a failure within the chain, for example, in case of lack of quality. The third most represented technology is sensors (46 papers), whose operation is based on measuring physical inputs and converting it into data with the aim of detecting changes in the environment. IoT functioning is often based on a system of sensors, which is reflected in the

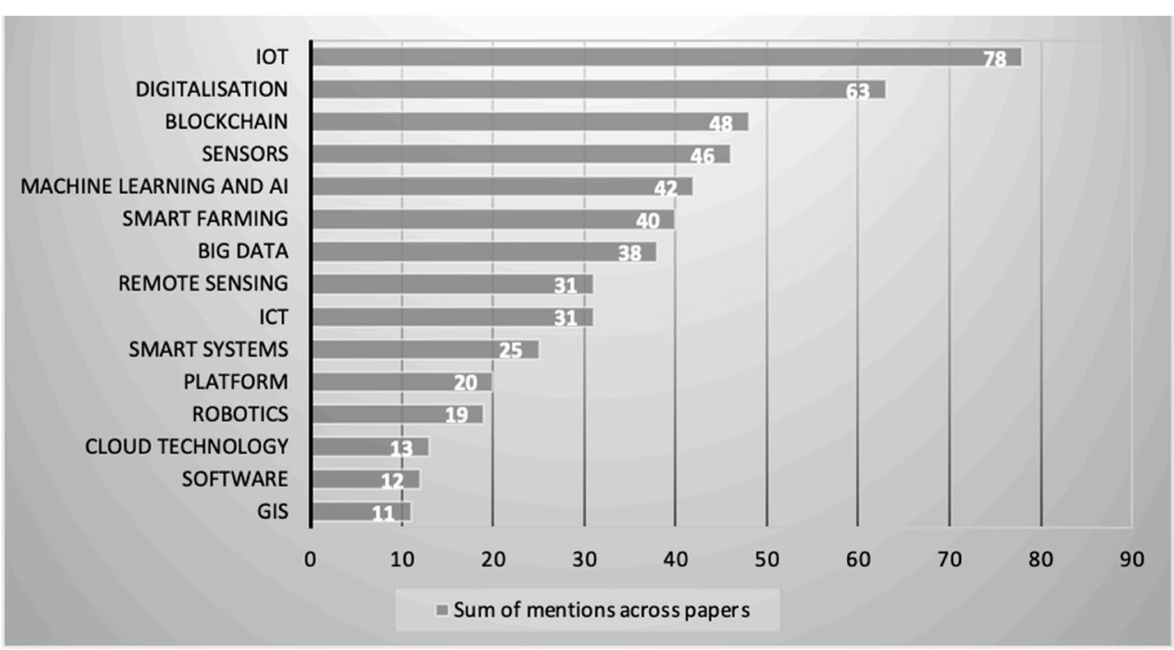

Fig. 5. Distribution of technologies.

presentation of both technologies in a high number of papers.

The category of smart systems (25 papers) incorporates sensing, actuation, and control in order to describe and analyse a situation, and then makes decisions based on data. This category includes smart packaging (i.e. Kabadurmus et al., 2023), smart city technologies (Schwindenhammer and Gonglach, 2021) and other systems based on data-driven decision making. Smart systems are often discussed alongside other technologies such as IoT, artificial intelligence (AI) and machine learning (ML). Even if a geographic information system (GIS) (11 papers) is a computer system, as well as a software, it is identified in a specific category due to its wider representation within sustainability aspects in agri-food.

While both academic literature and policy documents provide information regarding reasons and motives for choosing digitalisation in general and aiming at transforming digitally organisational and structural landscape in agri-food, the explanation of choice of a specific technology is limited. Mainly, analysed policy documents do not focus on individual technologies and tend to stay within the general digitalisation (Agri-food 4.0, precision agriculture and farming, and else) discourse.

While the Agri-food 4.0 presupposes the use of a certain smart technology, its choice and application should correlate with technology's characteristics and anticipated outcomes. Various digital and smart technologies differ not just by their technical characteristics and operation but also by the predicted outcomes on environmental conditions, social relations, and economic transactions, which are discussed later in the section. Moreover, their implication requires different resources provision and financial support for the primary installation and continuous maintenance. Therefore, for the practical implementation of one or another technology just its accessibility is not enough. It also requires sufficient knowledge of the specificity of their usage for successful performance.

5.1.3. The implementation of a digital technology: a functional approach

A supply chain in general can be defined as 'the interconnected journey that raw materials, components, and goods take before their assembly and sale to customers' (McKinsey, 2022). To compare, Cambridge dictionary defines supply chain as 'the system of people and organisations that are involved in getting a product from the place where it is made to customers'. Merging these two types of definitions - goods and people oriented - is important to investigate the diversity of elements within the system's functioning. The effective supply chain should be cost-effective, functional, ensure high quality of services, and socially responsible (Lichocik and Sadowski, 2013).

The agri-food supply chain consists of several interconnected and continuous nodes and operations, which support the system's functionality. Generally, the configuration of an agri-food supply chain is standard to a certain degree and consists of several main nodes, such as production, distribution, consumption and other. Each node, or segment, performs certain functions, which are crucial for the operation of the supply chain as a whole. The nodes' characteristics define its capacity and attributed functioning capabilities, and 'nodes with different attributes have different functions' (Zhao et al., 2021). The requirements to perform a certain function poses functional boundaries on different levels, which might affect the integration processes within a supply chain (e.g., Zacharia et al., 2014).

The analysis of digital technological applications within a supply chain can provide important insights in the boundaries of their impacts and associated outcomes. The application is understood, firstly, through its integration in the functioning of one or more nodes. Secondly, it is taken through the engagement of certain groups of actors and stakeholders. The dataset covered application of digital technologies across all supply chain's nodes, although a large number of papers focuses not on specific nodes but on the supply chain (and its management) in general or the agricultural and agri-food sector in general (123 and 57 papers respectively). A number of papers referred to both supply chain and certain node(s) at the same time. The distribution of digital technologies' applications across the supply chain's nodes is presented in Table 4.

While the digitalisation of the farming node is largely investigated (362 mentions), the other segments of the supply chain were significantly less covered within the dataset. The same tendency is observed in the documents that wholly cover digitalisation in farming (all 35 sources). IoT is the most popular technological solution for the production stage, as well as digitalisation in general. In contrast, the least applied technologies are software and GIS. While these technologies have in general not received much coverage in papers, their applications for farming are still the most representative ones.

Another supply chain segment with extensive coverage is distribution, logistics and transportation (114 records). The second most important technology for this node is blockchain, which proposes advantages for functional performance of all nodes.

While farming and distribution are crucial for food supply chains, other stages are also essential to maintain the continuity and coherence within the supply chain. In contrast, storage and packaging segments have the least number of representations in the dataset (21 and 10 respectively). Again, IoT as the most popular technology offers solutions at these stages. While there is a growing interest in digitalisation of storing and packaging of goods, our dataset does not reveal yet those achievements.

In particular, marginal attention is dedicated to the role of manufacturing, supply and provision of the inputs despite its essential role in sustaining all nodes with resources, services and means of production. Moreover, the provision segment includes supply of digital technologies, devices, and services. Such an under-investigation of digitalisation's potential at these stages in particular and at all nodes of the supply chain creates barriers to the complex and coherent digitalisation of the industry. In this way, the potential of various novel technologies to widen its application sphere alongside the agri-food supply chain requires a deeper investigation from not only policymakers and industry managers, but also academia.

Unlike the other technologies, IoT and blockchain have been largely applied within nodes of the agricultural supply chains, including farming and crop production, harvesting, processing, storing, distributing and retailing, consumption. This represents the widest technological implementation within different nodes of a supply chain. However, this is related to the character of the technology itself which application's value rises with wider use within transactions. Therefore, possibilities of integration of a technology alongside the whole supply chain are also framed by its characteristics and performance capabilities. Hereby, the discussion of digital technological deployments is focused majorly on farming or production node (in particular, through focus on smart farming) and consumption, as well as on the supply chain and sector in general without discussing in greater detail digital advancement of other nodes.

A complete or partial digitalisation of the supply chain can increase its efficiency, cost-effectiveness, functionality, quality of goods and services, and social responsibility (e.g., Attaran, 2020; Perano et al., 2023). Specifically, the increase in efficiency and cost-effectiveness is based on optimization and integration of operations and interactions. Furthermore, digitalisation provides wider access and connectivity, which transform the established functional boundaries.

5.1.4. The implementation of a digital solution: towards a multi-actor approach

Traditionally, actors and stakeholders are associated with specific supply chain's nodes and their functional capabilities. Applying a multi-actor perspective, the agri-food supply chain's composition involves a variety of actors' networks, whose functions and interactions go beyond the specific node's functions and functional boundaries. Digitalisation transforms not only the existing functional order at all system levels, but also the networks of actors and their interaction channels. Actors and

Table 4
Representation of digital technological applications within the supply chain.[a].

Technology/SC node	Supply/ provision	Production (incl. farming)	Processing	Storage	Packaging	Distribution (incl. logistics)	Trade and retail	Consumption	Supply chain	Sector in general	Unspecified
Smart farming	0	37	1	0	0	2	0	3	6	3	0
IoT	1	59	12	4	2	21	7	13	14	8	2
Blockchain	2	26	9	4	1	18	9	11	26	2	1
Remote sensing and UAV	0	25	1	0	0	5	0	3	4	3	2
Big Data	0	27	3	1	2	7	2	7	8	5	1
ICT	2	24	2	2	0	8	2	5	4	4	0
Machine Learning and AI	0	29	4	3	0	9	3	5	8	5	1
GIS	0	7	0	0	0	2	0	1	2	3	0
Robotics	0	15	2	1	1	5	2	5	3	0	1
Sensors	1	33	7	4	2	13	7	10	10	2	1
Smart system	0	13	1	1	2	6	3	4	7	5	0
Cloud technology	0	9	1	0	0	3	0	2	5	0	0
Platform	1	10	1	0	0	6	2	5	6	0	0
Software	0	7	2	1	0	4	0	3	3	3	0
Digitalisation	2	41	1	0	0	5	0	5	17	14	1
TOTAL mentions	*9*	*362*	*47*	*21*	*10*	*114*	*37*	*82*	*123*	*57*	*10*

[a] In the analysis, the number of papers presenting different technologies overlap because some papers presented more than one technology. Therefore, in Tables 4 and 5 the number of items is greater than the total size of the dataset (254 papers).

stakeholders, in their turn, affect the process and performance of digital applications. Therefore, actors hold a central position in the development and application of a strategic approach.

The research has identified several groups of actors and stakeholders within the agri-food supply chain, which are engaged in the digital applications. It distinguishes groups of internal actors (as inputs' suppliers; producers or farmers; processors; distributors, including logistics operators, logistics and transport solutions' providers; retailers and traders; consumers and customers), external groups (government actors and institutions, policymakers, local or regional municipalities and authorities; rural, sustainable, and other communities, agri-cooperatives, and public; scientific and academic communities, associations, researchers, experts, advisors) and the "other stakeholders" group (ranging from experts, advisors, and scientists, students, also NGOs and activists, as well as to engineering managers, and companies involved in the web-content analysis (for example, Latino et al., 2021). Moreover, the presence of engineers and managers of digital technologies and services in the analysed papers and documents was not significant enough to be distinguished as a separate group. The distribution of the various actor group's engagement across the technological applications are represented in Table 5.

The largest engagement across applications of all digital technologies is presented by farmers and producers (347 records). They are mostly involved, or affected, by digitalisation in general, IoT and smart farming, and with the least involvement in cloud technology and computing applications. This great number of records matches the record for applications in farming and production. In such a way, we can observe a structural imbalance towards farming and farmers in digitalisation of a

Table 5
Representation of various actor group's engagement in digital technological applications.

Technology/ Actors	Supplier	Producer (farmer)	Processor	Distributor	Retailer	Consumer	Government and policy actor	Communities	Experts and scientific community	Other stakeholders	Unspecified
Smart farming	2	34	0	0	1	10	6	4	8	4	0
IoT	4	44	7	5	7	16	8	5	3	12	12
Blockchain	10	30	8	10	11	28	7	1	2	13	9
Remote sensing and UAV	2	26	0	0	0	8	5	0	0	3	3
Big Data	3	23	3	2	5	12	5	3	3	6	6
ICT	3	22	1	2	2	8	5	2	2	3	6
Machine Learning and AI	3	32	7	3	7	14	7	4	2	8	5
GIS	0	9	0	0	1	1	0	1	0	1	1
Robotics	3	14	0	1	2	6	3	0	1	4	1
Sensors	5	29	5	5	8	20	7	2	1	10	6
Smart system	0	14	1	2	4	13	2	2	0	5	3
Cloud technology	2	6	2	2	2	6	1	2	1	1	2
Platform	2	10	0	1	2	11	4	1	0	3	3
Software	2	9	2	1	2	5	2	0	1	2	0
Digitalisation	8	45	2	3	2	16	4	2	3	11	8
TOTAL mentions	*49*	*347*	*38*	*37*	*56*	*174*	*66*	*29*	*27*	*86*	*65*

supply chain, which is presented in both papers and policy documents.

One of the most represented groups of actors - consumers and customers (147 mentions) - is also engaged in applications of all presented digital technologies. Such attention to consumers is in contrast to a smaller representation of consumption as a node. The similar trend is observed in policy, where both Green Deal and F2F documents consider various actors, including consumers, and their engagement with digital and sustainable food systems, while sidestep wider analysis of the consumption segment. This shows that while the implementation of digital technologies at consumption is limited, the engagement of consumers in digital applications at other nodes is rather common.

An opposite situation is observed for the distribution segment and the group of distributors. While the applications for distribution operations are well discussed in papers (but not in policy documents), the mentions of actors' engagement is significantly less (only 37 records). Their involvement in application of different technologies is also uneven: foremost, it is the integration of IoT. To compare, while such technologies as remote sensing and UAV, platform, and software are integrated at distribution node, analysis shows none or one actor engaged in such digital integrations. We are convinced that such a gap does not represent the real absence of actors in these applications. However, to a greater extent it does uncover a significant deficiency in the attention attributed to those actors and their activities.

Moreover, the gap in embracing various actors within the supply chain is crucial since it leaves not only physical machinery suppliers underrepresented, but also providers of digital technologies, infrastructure and services. While they have already become part of the supply chain due to the growing integration of digital infrastructure, the attention of both policy and academic debate has not yet elaborated their role in sustaining various operations. Digital suppliers provide smart and connected products that involve three types of components: physical (such as mechanical and electrical parts), smart (sensors, software, controls and else), and connectivity components ('that enable communication between the product and the product cloud, which run son remote servers and contains the product's external operational system') (Porter and Heppelmann, 2015). Moreover, they assist data collection, storage and management, and provide data analysis. Their inclusion in the understanding of supply and value chains is crucial due to, first of all, a different role played by digital innovations compared to traditional machinery: their impact on operations and transactions goes far beyond the (physical) implementation scope. The integration of a certain technology to some operations affect actors and their interactions within the whole system since not only supply chains are organised based on connectivity but also digital systems.

Overall, there is a significant difference in distribution of smart technological applications according to engaged actors and supply chain's nodes in both academic and policy papers. The multi-actor approach allows to identify and analyse the greater diversity of actors compared to the functional approach to the supply chain. The role of actors and their networks is not limited to the integration of digital solutions for operations and transactions within supply chains but also affects the development of the sector's sustainability. First of all, actors' behaviour towards digital technologies and their management will affect how widely and deeply technologies are integrated (Weltin et al., 2021). Secondly, the actors' behaviour will affect their decisions to reproduce (or not) certain applications of a digital technology. In such a way, a combination of functional and actor approaches is a prospective analysis of the integration process of digital technologies in agri-food systems.

The operations and transactions within agricultural supply chains have become more complex and interconnected, with digitalisation also affecting value creation. The increase in complexity is accompanied by widening of engaged actors and stakeholders, which has become reflected in the composition of agri-food value and supply chains. Nevertheless, the new actors are under-represented in both academic and policy debates. Even despite the focus of Farm to Fork strategy on food ecosystems, which are based on interconnectivity of stakeholders and operations, the initiative barely refers to the suppliers' functions and activities (usually, term suppliers are used to characterise farmers as 'food suppliers'), as well as to those of traders, retailers, and distributors. Among other stakeholders, EU Green Deal and F2F documents target the role of communities, in particular rural and young communities, and cooperatives in addressing sustainability challenges through digitalisation (18 mentions).

The deficit of attention on the diversity of stakeholders and their networks can affect not only current digital applications and the level of their integration but also future outputs, specifically sustainability outcomes. The identification of various actor groups and forms of their engagement is perceived as one of priorities for policy makers to design efficient activities. The cooperation of actors is crucial to build a stable and resilient agri-food system, 'in which no one is left aside and the responsibilities of market failures are tackled instead of unloaded onto some actors of the chain, often the weaker ones (e.g., producers)' (Contini et al., 2020).

In general, the factors such as reasons behind the decision for digitalisation, choice of digital technology, the application within the agri-food supply chain, and engagement of various actors and stakeholders affect the sustainability of the sector and supply chain. A limited application based on an offset towards a certain chain's node and certain actor group affects the scale of contributions to sustainability in general or one of its dimensions. The variety of aspects within sustainability dimensions as the achievements of digital transformation are discussed in the next part.

5.2. Linking digitalisation to sustainability: the sustainability pillars approach

A strategic approach essentially incorporates an evaluation of performance and results relative to the set goals and objectives. This assessment is important not simply to evaluate the effectiveness of a strategy itself but also to measure the progress and responses to changing conditions. Since the necessity to address the sustainability challenges has been one of the drivers of digitalisation expansion in the agri-food sector, its effectiveness can be evaluated on the basis of sustainability-related outcomes or outputs.

To unpack the contributions of digital technologies into the large and complex phenomenon of sustainability, our research analyses it through its dimensions or pillars. In turn, the outcomes brought by digital technologies are framed by the specificity of each technology, the sphere and scope of its application within the supply chain and the involvement of different actors. The further discussion of sustainability outcomes is based on application of specific technologies within a supply chain as discussed in previous sections. While most novel technologies contribute to addressing the global challenges such as climate change and food insecurity, largely discussed in both dataset and policy reports, our analysis focuses on more specific and localised outcomes. These outcomes were conceptualised through aspects of sustainability dimensions. To put in other words, through thematic analysis we have identified several main aspects, which compose each pillar.

5.2.1. The environmental dimension

The contribution to the environmental or ecological sustainability dimension is the largest and is concentrated on five main aspects and an unspecified category[1] (28 papers). The core is related to reduced consumption of resources and land appropriation, as well as to control and

[1] The category unspecified means that no mentions of any aspects of this pillar were identified in a paper.

reduction of the use of chemicals, antibiotics, and synthetic chemical fertilisers (117 records[2]). This aspect is also beneficial for the health of both consumers and farmers and is related to the social dimension of sustainability. The main contributions are brought by the integration of IoT (47), multiple technologies (36) and sensors (27), which allow to collect data and inform the resources' use based on its analysis. For example, IoT-based new modes can easily save more than 15% energy compared with its traditional production process (Song et al., 2021). If all technologies contribute to consumption, blockchain and AI and ML make also a significant difference (both with 23 mentions).

The second largest aspect is a reduction of environmental impact in general, in terms of carbon footprint and of GHG emissions in particular (108 papers) thanks to the adoption of multiple technologies and IoT (38 and 34 mentions respectively), as well as Big Data and Blockchain (23 and 21 mentions). This is also the more articulated impact of digital technologies in policy documents (all 35 records). As one of the main environmental challenges, it is also a primary reason to invest in digital solutions, as specified in several documents. All of the analysed technologies have a real or potential effect on the decrease of environmental impact, in particular on the farming stage, with the least involvement of GIS and software (limited to 2 and 3 mentions).

The third ecological aspect is related to waste management with 95 records. The main technology to improve waste management is IoT (40 out of 78 for the mentions of the technology in general). Blockchain and multiple technologies can bring some significant impact as well (28 and 24 records respectively). Also, half (23) of the total mentions of sensor technology is related to this aspect. Smart solutions can considerably decrease food waste through establishment of food-sharing initiatives and platforms. And the more actors are engaged in such initiatives, the larger is the distribution network.

The fourth aspect is dedicated to the enhanced environmental protection and prevention of unwanted changes to ecosystems (86 papers). The most significant change can be brought by IoT (25), multiple technologies (24), and smart farming (20). Also, 7 out of 11 records of the GIS applications refer to this aspect. The least articulated aspect is food certification, which includes higher certification, regulation standards and preservation of product's quality (sum of 21 mentions). This aspect is closely linked to the social sustainability pillar, which encompasses food security and safety. As expected blockchain (16 mentions), and IoT (8) are mainly applied to certification.

5.2.2. The economic dimension

The economic dimension of sustainability can be conceptualised through six critical aspects (164 records) and 15 records are unspecified. The most significant outcome of economic sustainability is the increase in efficiency and reduction of resources use (in economic terms) (154 records). IoT (56 out of 78) and AI and ML (33 out of 42) contribute to this aspect the most, followed by a combination of multiple technologies (40), blockchain and smart farming (both 29 mentions). The efficiency is based on better maintenance of resources and inputs and optimization of product life cycle, which is closely related to decrease in investments and various costs. Technologies can boost agricultural efficiency also through enhancing farmers' decision making, performance and planning capacity, which, among other, help farmers to save time (Lioutas and Charatsari, 2020). These results are provided due to the increased precision but also greater amounts of information and new ways to interact with customers directly (e.g., Ciruela-Lorenzo et al., 2020).

The second aspect, which is closely related to efficiency, brings costs and expenses reduction, which allows to maximise profits (129 records): we refer mostly to IoT and Blockchain (48 and 31 mentions respectively), and to smart farming and Big Data (20 and 19 respectively). Moving to the increase of productivity (96 records), the main contribution is brought by IoT (33) and combination of several technologies (29). It is a notable outcome for robotics (12 out of 19), smart farming (22 out of 40), and AI and ML (22 out of 42 mentions).

Then, the integration of digital technologies can increase the creation of economic opportunities (68 records), which include new jobs, business opportunities, novel business models, provision of market access and others. Since market access and information costs are among the most critical challenges for many actors, in particular smallholder farms, this contribution can affect the entire sector's configuration. The expansion of the horizon of possibilities is supported mostly by blockchain technology and IoT (both have 25 mentions). Moreover, it is a sphere for cloud computing to adopt its capabilities.

The fifth aspect of economic sustainability is increase in overall competitiveness and expansion of a competitive advantage (59 records). In terms of comparison, blockchain and IoT again make the largest contribution (23 and 18 mentions respectively). For the overwhelming majority of technologies, it is not a notable area of their impact, apart from software (half of mentions). Also, digital technologies provide actors with mitigation of various economic risks and uncertainties, which are often related to changes in market state and conditions (44 records). As for the previous aspect, blockchain and IoT have the largest number of records (18 and 17), while for all technologies it is not a significant area of contribution.

5.2.3. The social dimension

The social sustainability pillar is the least discussed in terms of technological contributions (111 records) but at the same time it is the most diverse in its aspects. It is composed of eleven aspects and an unspecified category (85). The central and most crucial one is the ability to increase food safety and security (59 mentions), which generally refers to higher quality and amounts of food and its access, presumably provided by a combination of different technologies, each of them solving specific problems such as the use of geo-spatial big data approach for crop yield estimation or smart irrigation forecast using satellite observation (Goel et al., 2021). Sustainable food systems are not only providing availability of food or sufficient food production and access to it but also the stability and foreseeability of these conditions (Helland and Sörbö, 2014). It is a particularly notable area of improvement for blockchain (27 out of 48), also for IoT (28 mentions). The smallest impact is identified for GIS, software, and smart farming.

The second largest social aspect is the improvement of labour conditions, in particular occupational health and safety (48 records). The most significant impact is brought by a combination of multiple technologies (19 mentions). While for most technologies it is a sphere of application (apart from GIS), the impact has not been perceived as significant for those applications. The impact of blockchain is not identified as notable (9 out of 39), although this technology is expected to be one of the leading ones in this area. It tracks employees' health conditions and their infection risk and identifies possible absenteeism resulting in bottlenecks and warns the entire system to take prompt measurements (Kayikci et al., 2022). It also can further warrant compliance with human rights and safer work practices by restricting malpractices (Mukherjee et al., 2022). A fundamental change of work conditions is accelerating the transition from informality to formality brought about by various technologies, in particular digital identification. An important labour impact brought by the novel technologies is in decreasing farmers labour time and their stress.

The third important aspect is the improvement of wellbeing (as a combination of physical, mental, emotional and social health factors), welfare and health conditions (not occupation related), including animal welfare (44 records). This change can be facilitated, in particular, by robotics (8 out of 19), IoT and other technologies. Another aspect is the provision of access (also 44 records) to various services and resources, including knowledge, data, information, know-how, but also food, communities, networks and others, secured in one way or another by all

[2] The numbers represent the total mentions counted according to each sustainability aspect. They differ from a sum of mentions by each digital technology, because each aspect is covered by several technologies.

the technologies due to their various characteristics, has a potential to dramatically change food systems. None of the technologies show a significant impact in this area, while all of them still contribute slightly (apart from GIS and software with 0 and 1). Aspects of agri-food's social sustainability also encompass increase in level of trust, accountability, transparency and traceability within the supply chain (39 records), which is majorly provided by blockchain (27 mentions). Other technologies have fairly small input in trust building, especially GIS, smart systems, robotics, software, and ICT.

The aspect of widening participation and social inclusion (43 records) is mostly supported by IoT, ICT and a mix of technologies (15, 13, 10 mentions respectively). This aspect is closely related to the increase in social capital (27 records) through expansion of social cohesion, safety nets and social networks based on formal and informal interactions. An important contribution can be made by digital platforms, in particular those 'that have a social character that aim to promote the use of applications as a technological tool at the service of citizens, acting through collective social commitment' (Cane and Parra, 2020, pp. 1660). While some contributions are made by smart farming, a number of technologies do not show a notable impact (such as GIS, sensors, remote sensing, and cloud computing). However, both of these aspects are crucial for community development, especially in rural and lagging areas, and nourishing of sustainable and resilient, well interconnected communities, which will reproduce sustainable practices.

The aspect of the access' provision to various services and resources, including knowledge, data, information, know-how, but also food, communities, networks and others (44 records), secured in one way or another by all the technologies (except for GIS) due to their various characteristics, has a potential to dramatically change food systems. Mostly this aspect is secured by IoT, blockchain, and smart farming (16, 12, 11 mentions respectively).

The last but not the least social aspects include, firstly, contribution to development of social innovations (22 records), for example, 'through agroecological principles like local knowledge and biodiversity' (Lajoie-O'Malley, et al., 2020), facilitated by smart farming, blockchain and a mix of technologies. Secondly, it is the reduction of various social risks, including issues related to living conditions, safety, human rights (15 records). This aspect is closely related to poverty reduction (14 records), since it is one of social risks, as well as one of the global challenges. In this context, Mhlanga (2021) discovered that AI reduce poverty through improving the collection of poverty-related data through poverty maps. Laso Bayas et al. (2020) highlight the importance of adopting a freely available app that allows farmers (also the smaller one who cannot afford consultancy services) to measure and monitor specific indicators enhancing land productivity and improving their nutritional status. In these areas, the impact created by each technology has shown little significance because it is quite recent, with some contribution brought by IoT and blockchain (less than 10 mentions for both).

Hence, the choice of a particular smart technology to be implemented within an agri-food supply chain will affect different operational dimensions, which will result in diverse sustainability outputs. Therefore, a clear identification of a complex of the existing challenges and problems in a specific part of the chain or its operation in general is required in order to select the most suitable digital solution. While the analysis of contributions by technological advancement to sustainable development is important, it is hard to connect it to the search for real solutions for managing digital transformation. The information regarding the benefits of technologies in general does not inform the actors involved in their applications about technology's use and (possible) outcomes since they have been attached to a specific technological solution. Therefore, academia, industry and policymaking are likely to benefit from more profound research on technological inputs in sustainability within supply chain's nodes and involved actors.

5.3. *Towards the twin transition? A strategic approach*

Policy initiatives devised and deployed by a variety of institutional actors are among the major drivers of incorporation of smart and digital technologies in agriculture's operations and transactions. At different levels, from global to local, institutions highlight the necessity to employ the advantages of digitalisation in all economic sectors, with agriculture and agri-food being no exception. Several policy initiatives address the usage of smart technological innovations to tackle the expanding global challenges, such as food insecurity and climate change, and to invest in sustainable development.

Nevertheless, despite the potential of digital tools in agriculture, the adoption rate in Europe is still low due to strong barriers, and 'adoption depends on a wide range of variables such as farmer characteristics, farm structure, location, and organisational, institutional, and information factors' (Scuderi et al., 2022). There are growing challenges regarding implementation of digital technologies in agricultural operations and the outcomes they bring on socio-economic activities and relations. The main concern though has been regarding their uniform provision with benefits and advantages compared to traditional ways of managing operations and transactions. The implementation of smart technology in the agri-food supply chain does not promise to solve the challenges and problems simply through the availability of the innovation, although technological accessibility is still an issue in many developing and developed countries. Moreover, there is a lack of coordination in technological applications among stakeholders, and 'businesses engaged with it face challenging decisions whose outcomes will affect their own future directions and those of the agri-food sector' (Mahmad et al., 2022).

One of the ways to address the existing challenges for agri-businesses is to develop a strategic approach to digital transformation. It encompasses envisioning, goal setting, resources allocation, and prioritisation or strategic trade-offs. Development of digital strategy, which is aligned to the firm's business strategy and vision, should assist actors in the appropriation of digitalisation and motivate them to reproduce the behaviour related to the use of technologies. In other words, a clear understanding of the necessity of technological implementation, its adoption to the firm's vision, appropriate resource management is supposed to motivate the actors to aim at technological use in the future. In such a way, it should contribute to spreading and managing the digital transformation of a firm in particular and the sector in general.

Following the theoretical approach to digital transformation, our research underlines the importance of people, as noted by Chamorro-Premuzic (2021), or actors and stakeholders, in managing the application of digital technologies and subsequent changes. Actors are those people who facilitate the applications of digital solutions and manage their operational capacities, as well as those who experience the changes. This social essential component refers not simply to people's engagement or access to technology and its outputs. Managing digital transformation should encompass educational activities to expand the knowledge regarding digital applications among engaged actors. The attention given to diverse actors should be expanded in both academic and policy debates to expand the insights in their engagement in the digitalisation processes.

Digital transformation is about bringing novel ways of interactions and transactions, and to become continuous; these ways are supposed to be integrated into the firm's and sector's set-up. In other ways, actors should be motivated to reproduce certain patterns of socio-economic development based on digital solutions. Often the motivation is not limited to their economic or ecological impact but encompasses also the effects on social sustainability. The targeted utilisation and adaptation of a certain technology or a mix of devices and solutions can improve labour conditions, reduce the need to perform dangerous tasks and reduce the number of accidents, while increasing trust levels among stakeholders. The focus on social sustainability within the sector should be incorporated in the development of various strategies at both micro (individual firm) and macro (collective industry) levels. In turn, the way how digital application has been managed affects largely their contributions to social, economic, and environmental sustainability dimensions.

In order to take into account social sustainability and effects on the social component of agri-food supply chain, we need to know which actors and stakeholders are engaged in technological applications and their consequent changes. A combination of a functional approach with a multi-actor perspective will provide a more comprehensive picture of changes within a supply chain. Digital transformation has brought fundamental changes in supply chain's operations and networks of the engaged actors. Digital technologies have brought connectivity and transparency on a new level, which allows to engage and connect a greater diversity of actors and stakeholders. Digital technologies, such as blockchain or ICT, can connect stakeholders without intermediaries, on the one hand, and include new stakeholders such as experts, scientists, communities and others, on the other hand. The rising complexity of actor networks, as well as data and information flows produced by them, require a strategic approach for effective management which leads to achievement of the set goals (for example, such as twin transition).

At the same time, policy documents provide limited information on institutional support for firms, in particular for small and medium size enterprises, to develop a strategic approach to digitalisation, which is based on both firm's characteristics and technology's capabilities. Policy documentation provides even less details on digital transformation management at the sectoral level, which is a priority for international institutions and policymakers. While policymaking in the sphere of agriculture and agri-food at the European level is currently focused on facilitating the twin transition, it does not present an articulated approach to manage it. In other words, the process of coupling digitalisation and sustainability into twin transition is not expected to happen naturally. It is reaffirmed also by the documents on twin transition, which underlines different natures of both phenomena and do not necessarily always align (e.g., Muench et al., 2022). In such a way, twin transition can notably benefit from adopting a strategic approach on different levels. It does not simply help to interconnect all the elements engaged in digital transformation into a complex and coherent system based on alignment and coordination. It also provides a roadmap for managing diverse changes related to digitalisation and sustainability. Moreover, the integration of a strategic approach can help in the expansion of sustainability outcomes and their aspects, in particular societal ones.

5.4. Future research directions

First and foremost, the granular definition of the loci of application of different digital technologies in supply chains allows empirical researchers to produce context-sensitive accounts and assessments. Our review, in fact, distils the current state of academic research and policy making at the European level on the positioning of digital technologies at the different stages of the agricultural and agri-food supply chains and on their effects, in particular those related to sustainability outputs.

However, what is missing from our investigation opens a number of potential avenues for further research into general and partial digitalisation of the agri-food supply chains.

- digital technologies that are underrepresented in literature and policy making, as well as the nodes of supply chains that were not enlightened enough, might be promising areas for action-research aimed at speeding up the adoption of technologies and at understanding the critical factors impeding or enabling their widespread adoption. One of the ways to develop it might be a matching analysis of the granularity of the conceptual treatment of digital technologies in policy-documentation, in reports and documents feeding it such as reports from major consulting firms and think tanks. Assessing the overlap or lack thereof might help scholars and policy-makers in understanding the degree to which policy-making has been driven by scholarly research or has unfolded along an independent path;
- to fully exploit the actual and potential advantages, smart mixes of technologies are required (Weltin et al., 2021). Companies and policymakers need to be aware of the impact of single technologies and entangle all the aspects that could hinder the implementation at the company level as well as at regional scale. There is a current significant gap in the literature about this issue. Therefore, studies that focus on specific technologies highlighting how they affect the supply chain nodes, the actors involved and other already implemented technologies must be encouraged. Findings might help companies to avoid various hidden costs and issues (e.g., high learning costs, economic benefit uncertainty, perceived incompatibility of technologies with the current one) by anticipating them. Moreover, they might assist policymakers in developing informed decisions and allocating funds to support specific actions;
- this research is focused mostly on two complex and multi-layered phenomena – digitalisation and sustainability, which are inherently independent from each other and their linking is rooted in the policy making and academic debates. This perception was reflected in the search strategy. However, nowadays the increasing attention towards linking both phenomena is conceptualised also through the introduction of novel terms, in particular twin transition (or transformation). Therefore, future research can expand the methodological toolkit by adding the new categories to investigate the manifestations, which those categories are aimed to identify and describe.

6. Conclusion

The potential of digitalisation's contribution to sustainability within agriculture and agri-food is wide and complex. However, digital solutions do not necessarily lead to contributions to sustainability. Understanding how to achieve the desired advantages requires that firms choose the most suitable technology based on their characteristics, capacities, and goals. At the same time, technological applications and their management depend on various factors, and so do also the sustainability outcomes at different levels. These factors consist of, first of all, reasoning for choosing digital innovations among other types of innovations. The identification of the reasons behind such a choice, which was our first research goal, could frame the achieved sustainability outcomes. The reasons should be grounded not only in existing policies but also in the firm's capabilities and vision. The choice of a specific technology is also crucial in improving productivity and efficiency, as well as in leading the agri-business towards social, economic, and environmental sustainability. The selection of one or several technologies will affect the transactions and operations and, most importantly, the goals' achievement.

While both academic literature and policy making documentation highlight the advantages brought about in agriculture and agri-food by digital technologies, they do not focus resolutely yet on the reasons for choosing one or another digital technology. Moreover, most of the technological characteristics and operations, as well as benefits of application, are not concerned in the context of specified local reasons. In such a way, further research into the reasoning can greatly advise policy makers, researchers and firms in terms of pressing issues and the most suitable and efficient options based on digital solutions.

The application of a chosen technology at a certain node and in given operations within the supply chain, our second research goal, will predetermine, among other, its contribution to sustainability. This contribution is also affected by the activities of the engaged actor groups that need to be trained and have access to knowledge. Online courses on the digital agricultural economy, such as in Hungary, can get farmers acquainted with digitalisation and innovation and improve the adoption of new technologies (Biro et al., 2021). Hence, the complex process of linking digitalisation and sustainability into twin transition can be supported by a strategic approach, which organises all the elements into a complex and coherent system. To understand the sustainability outcomes brought by digitalisation in the agri-food – our third goal, our research has utilised the framework of three sustainability pillars alongside a strategic approach. This integrated approach allowed us to investigate the phenomenon in its complexity and develop a holistic approach.

Our research has identified a structural imbalance in the investigated technological integrations within a supply chain in terms of both functional nodes and engaged actors. This significant imbalance towards farming nodes and groups of farmers allows to claim the partial nature of supply chain's digitalisation. Uneven technological applications at both supply chain nodes' and actors' levels limit the potential advancement of specific nodes and integration of a wider range of actor groups. In turn, such uneven applications frame the associated sustainability outcomes, which are identified as aspects of sustainability pillars. The research shows that the contribution of each digital technology to sustainability is manifested in a combination of those aspects.

Our results contribute to a complex investigation of digital transformation and its relations to sustainability. To specify, a deeper understanding of a relation between specific technologies and their associated sustainability outputs develops at academic, policy and management levels a more elaborated motivation for their implementation. In the sphere of policy making in the agri-food, this research can advise the urgence of a strategic approach at the micro, meso and macro levels. The role of policy makers and especially local authorities in this process could be in providing assistance in strategic development for various local agri-businesses. The knowledge of the policy makers of the local sector's can be combined with the firm's characteristics to design an appropriate strategy of digital transformation. Such support or service provided by the local authorities can also include other stakeholders and actors, who have already been included in the agri-food supply and value chains.

CRediT authorship contribution statement

Alena Myshko: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization, Software. **Francesca Checchinato:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization, Software. **Cinzia Colapinto:** Writing – original draft, Visualization, Validation, Supervision, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization, Resources, Writing – review & editing. **Vladi Finotto:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization, Software. **Christine Mauracher:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization, Software.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Alena Myshko reports financial support was provided by Ca' Foscari University of Venice.

Data availability

Data will be made available on request.

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