Driving sustainable agri-food supply chains through Industry 4.0: A multidisciplinary collaboration

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Abstract Although Industry 4.0 (I4.0) adoption and agri-food supply chain (AFSC) sustainability are widely discussed, there remains a lack of an integrated framework to illustrate the I4.0 adoption process. Grounded in the Technology-Organization-Environment (TOE) framework, this study explores the drivers of I4.0 adoption for enhancing AFSC sustainability through interviews with 16 AFSC practitioners, analyzed using thematic analysis. Our findings provide novel insights that extend existing research. First, this study confirms I4.0 adoption in AFSCs is a collaborative effort involving multiple stakeholders, including I4.0 technology manufacturers, government agricultural departments, and non-profit technological and knowledge service providers. Second, we find these stakeholders collectively mobilize technological, financial, knowledge, policy, and human resources across AFSCs to facilitate I4.0 adoption. Third, we identify 15 drivers of I4.0 adoption for enhancing AFSC sustainability. Notably, factors including the deployment of platforms for widespread information sharing and large-scale skill training for the next generation of farmers are rarely discussed in existing literature. Finally, we develop a four-layer "onion" framework illustrating the key aspects of I4.0 adoption, encompassing (1) primary AFSC stakeholders, (2) resources leveraged to drive adoption, (3) drivers of I4.0 adoption for AFSC sustainability, and (4) the specific I4.0 technologies adopted.

Keywords: Industry 4.0 adoption, sustainable agri-food supply chain, semi-structured interviews, thematic analysis, a multidisciplinary collaboration, an integrated framework

1. Introduction

Food is an essential necessity for life, supplying vital nutrients that support human growth, repair, and maintain good health. The global population is projected to rise over the next 30 years, growing from the current 8 billion to 9.7 billion by 2050 and potentially peaking at nearly 10.4 billion in the mid-2080s (Hassoun et al. 2025; United Nations. 2025). As a result, global food consumption is expected to surge by over 50% and possibly by 70% by 2050 (Dijk et al. 2021). Consequently, the environmental effects of the agri-food production system are likely to increase by 50% to 90%, surpassing planetary boundaries that define a safe operating space for humanity (Springmann et al. 2018). Considering the challenges posed by resource degradation, unsustainable agricultural activities, and the growing demand for nutritious and healthy food, the Food and Agricultural Organization (FAO) (2022) highlights that innovation is a key catalyst for transforming the agri-food system and advancing sustainability.

Industry 4.0 (I4.0), also known as the Fourth Industrial Revolution, refers to the intelligent networking of machines and processes through cyber-physical systems (CPS), combining digital, psychical, and biological disciplines (Xu et al. 2021; Hassoun et al. 2024a). It encompasses various technological innovations that seamlessly integrate humans, machines, and manufacturing processes by enabling real-time information flows, thereby enhancing coordination, cooperation, and collaboration across different stages of production while aligning with consumer demands (Olan et al. 2024; Zhao et al. 2025a). Key I4.0 technologies include CPS, the Internet of Things (IoT), big data analytics, cloud computing, artificial intelligence (AI), blockchain, automation and industrial robotics, simulation and modelling, visualization technology, and additive manufacturing (Zheng et al. 2021; Rejeb et al. 2024b). These advancements play a crucial role in transforming traditional agri-food supply chains (AFSCs) from resource-depleting, inefficient, and environmentally harmful into resourceconscious, efficient, and sustainable industries (Hassoun et al. 2024b). AFSCs encompass the interconnected stages from farm to fork, including production, processing, distribution, retailing, and consumption (Liu et al. 2021; Chen et al. 2024). Zhao et al. (2024a) highlight that I4.0 technologies contribute to the economic, social, and environmental dimensions of AFSC sustainability. Key benefits include improving water and fertilizer use efficiency, reducing labor costs, lowering carbon emissions, and decreasing work intensity. Similarly, Yadav et al. (2022) review the application of I4.0 technologies in AFSCs, demonstrating their role in promoting sustainability through enhanced information and advisory advice, process innovation, smart packaging, waste reduction, and optimized delivery channel management. Percin et al. (2025) further emphasize the adoption of I4.0 technologies in AFSCs positively impacts resource efficiency, waste and emissions reduction, supply chain connectivity, traceability and transparency, and stakeholder's right, thereby contributing to AFSC sustainability. Despite the promised benefits of I4.0 technologies for sustainability, their adoption remains low in the agri-food industry (Zhao et al. 2023). According to the latest survey conducted by McKinsey & Company (2023) on agri-tech adoption, farm management software has the highest adoption rate among farmers, with 21% having implemented it, followed by a 15% adoption rate for remote sensing and precision agriculture software. Compared to these two adoptions, sustainability-related solutions lag significantly behind, with only 5% of farmers utilizing tools such as carbon emission measurement and irrigation system optimization. A slight increase in the adoption of sustainability-related technologies may be foreseen over the next five years.

The remarkably low adoption rate of sustainability-related I4.0 technologies in AFSCs prompted us to investigate the driving factors that enhance the situation. We formulated two research questions: (1) what are the drivers that facilitate the adoption of I4.0 technologies for AFSC sustainability; and (2) how can these drivers be effectively leveraged to establish I4.0-enabled sustainable AFSCs? To address these research questions, grounded in Technology-Organization-Environment (TOE) framework (Dadhich & Hiran. 2022; Aniceski et al. 2024), we conducted in-depth interviews with Chinese AFSC practitioners who have adopted I4.0 technologies for sustainability purposes. The qualitative data collected was analyzed using thematic analysis to identify drivers and generate insights into how these drivers can be leveraged effectively. China was chosen as the research context due to its leadership in smart agriculture and its rapidly expanding market, which was valued at over $14.46 billion in 2024 (Textor. 2025). Advanced technologies such as IoT, big data, drones, and BeiDou Navigation Satellite System (BDS) are widely integrated into crop production, enhancing precision seeding, smart irrigation, and plant protection. Recent data highlights China's significant advancements in agricultural technology, with the contribution of agricultural and technology science to high quality agricultural development rising from 54.5% in 2012 to 62.4% in 2022. Additionally, the mechanization rate for crop cultivation and harvesting has surpassed 73% (CGTN. 2023), further demonstrating the country's commitment to technological innovation in agriculture.

This study makes significant contributions to both existing knowledge and managerial practices. First, it underscores the successful adoption of I4.0 technologies in the agri-food industry is a collaborative effort involving multiple stakeholders, including farmers, I4.0 technology manufacturers, non-profit technological and knowledge service providers, government agricultural departments, agricultural higher education institutions, research institutes, and focal companies within AFSCs. Second, these stakeholders collectively mobilize policy, knowledge and financial, technological, and human resources across AFSCs, leveraging various drivers to facilitate the adoption of I4.0 technologies. Third, this study develops an "onion" framework to conceptualize key aspects of I4.0 adoption, incorporating four interrelated layers: (1) primary AFSC stakeholders, (2) resources leveraged by these stakeholders to drive adoption, (3) drivers of I4.0 adoption for enhancing AFSC sustainability, and (4) I4.0 technologies implemented. This framework extends the applicability of the TOE framework by offering a more nuanced understanding of I4.0 adoption in AFSCs. Finally, this study identifies 15 key drivers of I4.0 adoption for enhancing AFSC sustainability, including several that are largely overlooked in existing literature.

The remainder of this paper is structured as follows. In Section 2, a critical literature review on I4.0 and supply chain sustainability is presented, identifying limitations of existing research. In Section 3, we illustrated and rationalized the research methodology adopted in this study, followed by the findings and discussion shown in Section 4. Finally, conclusions, limitations, and future research directions are provided in Section 5.

2. Literature review

In this section, we first examine the adoption of I4.0 technologies for supply chain sustainability. Next, we present the drivers identified in existing studies that positively influence I4.0 adoption in achieving sustainable AFSCs. We then review prior research that has applied the TOE framework. Finally, we identify research gaps to highlight opportunities for future studies.

2.1 Industry 4.0 technologies adopted to achieve supply chain sustainability

I4.0 technologies are widely reported to have a positive impact on supply chain sustainability. For example, Karmaker et al. (2023) highlight that I4.0 technologies significantly and positively impacts supply chain sustainability performance, with green supply chain management and circular economy practices serving as key mediators. Srhir et al. (2023) reinforce that advanced technologies such as blockchain and IoT have significantly increased the potential for supply chains to achieve sustainability goals. More specifically, Sislian and Jaegler (2022) and Tsolakis et al. (2022) argue that blockchain technology enhances supply chain sustainability by enabling faster transactions, improving traceability, and reducing waste and delays. Drawing from evidence in the automotive industry, Ghadge et al. (2022) highlight that a combination of I4.0 technologies, including additive manufacturing, cloud computing, blockchain, CPS, and automation and robotics, can drive green purchasing, supplier and customer environmental collaboration, green manufacturing, internal environmental management, and reverse logistics. In the context of AFSCs, Senturk et al. (2023) found that I4.0 technologies such as IoT, machine learning, data mining, smart sensors, and AI can be applied across various areas of the agri-food industry. These applications include predicting weather events, monitoring air temperature, humidity and soil moisture, enhancing irrigation efficiency, controlling pests, and optimizing pesticide use. Similarly, Zhao et al. (2019) investigated the role of blockchain technology in AFSC management and found that it plays a crucial role in ensuring traceability, enhancing information security, and supporting sustainable water management. Finally, Sharma et al. (2025) provide a comprehensive summary of 10 widely applied I4.0 technologies in AFSCs. For instance, augmented reality facilitates real-time visualization and risk mitigation, robotics and simulation improve operational efficiency, big data analytics enhance resource management, and AI optimizes precision agriculture and resource utilization.

2.2 Drivers facilitate Industry 4.0 adoptions achieving sustainable agri-food supply chains

In this section, we conducted a systematic literature review (SLR) to identify drivers for adopting I4.0 technologies to achieve AFSC sustainability. Keywords used in previous SLRs (e.g., Ghobakhloo et al. 2021; Yadav et al. 2022; Srhir et al. 2023; Arshad et al. 2025) pertaining to the areas of I4.0 and sustainable supply chain management (SSCM) were identified and used as search criteria to find relevant publications among the databases of Web of Science, Business Source Complete, Scopus, and Taylor & Francis Online. These databases were selected because they include the world's major journals, conference proceedings, and book chapters, with a strong focus on business and management, and have been extensively used in literature reviews (Zhao et al. 2024b). Keywords were combined as search strings for our database search: ("drivers" OR "enablers" OR "facilitators" OR "factors" OR "determinants") AND ("supply chain sustainability” OR “sustainable supply chain”) AND (“Industry 4.0” OR “digital” OR “supply chain 4.0” OR “digitalization”) AND (“food” OR “agri-food” OR “agriculture”). Our initial search across these databases retrieved 1,542 publications. To refine the results, we limited the research areas to business and management, reducing the number to 353 publications. We then applied two inclusion criteria: (1) the selected publications should be journal papers written in English that published in Academic Journal Guide 2024 (Chartered Association of Business Schools. 2024) ranked 3, 4 or 4* journals; and (2) the selected publications should have a clear focus on I4.0, AFSC sustainability, and the identification of adoption drivers. To ensure the relevance of the selected papers, two senior PhD students specializing in SSCM and I4.0 technologies reviewed each paper’s abstract, introduction, conclusion, and even the full paper. After this rigorous screening, 13 journal papers met our criteria were included in final analysis. Table 1 provides a detailed overview of these selected studies. Each paper was classified based on the five research methodologies distinguished: theoretical and conceptual papers, case studies/interviews, surveys, modelling papers, and literature reviews (Seuring & Muller. 2008).

Table 1 Empirical studies of I4.0 and AFSC sustainability

Author(s) (year)	**Topic focus/Journal published**	**Research methodology adopted**	**Theory adopted**	**Country focused**
Luthra et al. (2020)	Analysis of influential strength of drivers to deploy I4.0 to achieve sustainable AFSC (International Journal of Production Research)	Case studies/interviews Modelling papers	Not specified	India
Srivastava & Dashora (2022)	Modelling enablers for electronic traceability adoption in Indian AFSCs (Annals of Operations Research)	Case studies/interviews Modelling papers	Not specified	India
Despoudi et al. (2023)	Exploring the enablers and barriers to I4.0 adoption for circular economy implementation (Annals of Operations Research)	Case studies/interviews Modelling papers	Resource-based view	India
Yadav et al. (2023)	Blockchain drivers to achieve sustainable food security (Annals of Operations Research)	Case studies/interviews Modelling papers	Not specified	India
Annosi et al. (2024)	Exploring the nexus of digital transformation and sustainability in agribusiness (Technological Forecasting and Social Change)	Theoretical and conceptual papers	Not specified	Not specified
Stefanini & Vignali (2024)	The influence of I4.0 technologies on social, economic and environmental sustainability of the food sector (International Journal of Production Research)	Literature reviews	Not specified	Not specified
Trevisan & Formentini (2024)	Digital technologies for reducing food waste and loss (IEEE Transactions on Engineering Management)	Literature reviews	Not specified	Not specified
Vecchio et al. (2024)	Enablers of managerial practices for circular business models (IEEE Transactions on Engineering Management)	Case studies/interviews	Not specified	Italy
Wang et al. (2024)	Digital transformation in AFSCs (Supply Chain Management: An International Journal)	Literature reviews	Diffusion of innovation theory	Not specified
Zhao et al. (2024a)	Understanding the drivers of I4.0 to enhance ASFC sustainability (Information Systems Frontiers)	Case studies/interviews Modelling papers	Middle-range theory	China

Percin et al. (2025)	Evaluating the adoption of I4.0 to achieve sustainable AFSCs (Business Strategy and the Environment)	Cases studies/interviews Modelling papers	Not specified	Not specified
Silva & Sehnem (2025)	The utilization of I4.0 technologies to enhance circular economy (Business Strategy and the Environment)	Case studies/interviews	Stakeholder theory	Brazil
Zhao et al. (2025a)	Enablers to deploy I4.0 to achieve a circular in ASFCs (Journal of Environmental Management)	Case studies/interviews Modelling papers	Grand theory	China

Our review highlights a diverse range of drivers identified by scholars for adopting I4.0 technologies to enhance the sustainability of AFSCs. For example, Zhao et al. (2025a) reveal 27 drivers for I4.0 deployment to achieve a circular economy in China's AFSCs, including rural revitalization policy that empowers agricultural digitalization, large-scale training for new generation farmers, pressure from competitors, and government subsidies for enterprises to deploy I4.0 technologies. Similarly, Yadav et al. (2023) examine blockchain adoption for sustainable food security in India, highlighting 14 drivers such as ethical sharing platforms among agro-stakeholders, monitoring of agro-practices and processes, and secured and efficient transactions. Focusing on managerial practices, Vecchio et al. (2024) propose six drivers that positively influence circular economy business model design in an Italian agro-energy company, including national and supranational regulations for green energy production and public funding for new industrial installations. Meanwhile, Zhao et al. (2024a) offer a broader perspective, suggesting that AFSC practitioners adopt I4.0 technologies due to social, economic, and environmental benefits, such as reducing groundwater pollution, improving working conditions, lowering work intensity, and receiving government subsidies for agricultural facilities. Finally, Luthra et al. (2020) emphasize the role of I4.0 in diffusing sustainability across ASFCs, driven by enhanced information sharing systems, resource optimization, efficient workforce knowledge sharing, and greater transparency among stakeholders.

This study extends existing research by adopting a more comprehensive approach that considers all AFSC stakeholders, whereas prior studies have focused on only a subset. For example, Vecchio et al. (2024) based their findings on a single case study, while Luthra et al. (2020) derived insights from expert opinions limited to the agri-food manufacturing sector. Similarly, Zhao et al. (2024a) collected data from farmers, technology service providers, food processors, and logistics service providers but did not account for the agricultural government department and retailers. Building on these prior works, this paper integrates their findings into a holistic framework that not only identifies the drivers of I4.0 adoption for AFSC sustainability but also explores how to effectively leverage these drivers, providing a more complete and nuanced understanding of the factors influencing digital transformation in the sector.

2.3 Technology-organization-environment framework

The TOE framework, developed by Tornatzky and Fleisher (1990), is a theoretical framework that explains how the adoption and utilization of new technologies are shaped by multiple factors. These factors emerge from three domains: the characteristics of the technology itself, the organizational context in which it is implemented, and the external environment in which the organization operates. Scholars have widely applied the TOE framework to examine the factors influencing technology adoption across various industries and contexts. For example, Chittipaka et al. (2023) identified 11 key factors affecting blockchain adoption in emerging markets, including financial resources, competitive pressure, regulatory requirements, executive support, and relative advantage. Awa and Ojiabo (2016) explored the determinants of enterprise resource planning (ERP) software adoption in small and medium-sized enterprises (SMEs). Their findings suggest that determinants such as information and communication technology infrastructure, technical expertise, perceived compatibility, perceived value, security concerns, and firm size significantly impact ERP adoption. Xu et al. (2023) conducted a review on the role of technology in supply chain decarbonization through the theoretical lens of the TOE framework. Their study shows that organizational factors such as scope of business operations and firm size, environmental factors including regulatory pressures, stakeholder influence, and international policy requirements, as well as technical factors like renewable energy solutions, shape the pre-adoption phase of low-carbon management practices. Finally, Kalaitzi and Tsolakis (2022) examined supply chain analytics adoption in the UK manufacturing sector. Their findings indicate that environmental and organizational factors play a crucial role in influencing managerial decisions to adopt supply chain analytics, whereas technological factors have a limited impact.

2.4 Research gaps

Our meticulous review of prior works on I4.0 and AFSC sustainability reveals several research gaps.

First, several research methodologies are commonly employed to examine I4.0 adoption and AFSC sustainability, including literature reviews and the combination of case studies, interviews, and modelling techniques. For example, Despoudi et al. (2023) utilized case studies and interviews to identify enablers and barriers to I4.0 adoption for circular economy implementation, followed by modelling techniques such as total interpretive structural modelling to uncover the interrelationships among these factors. However, few studies rely solely on qualitative approaches, such as case studies and interviews, to gain an in-depth understanding of the drivers of I4.0 adoption in advancing sustainable AFSCs. This study addresses the gap by employing semi-structured interviews to collect qualitative data from Chinese AFSC practitioners and applying thematic analysis to identify drivers.

Second, theory has not been widely adopted in the investigation of this topic. This review shows 38.5% of the selected studies incorporate a theoretical foundation. Among those that do, middle-range theory, grand theory, stakeholder theory, resource-based view, and diffusion of innovation theory are commonly applied to examine I4.0 and AFSC sustainability, while the TOE framework remains underutilized. A robust theoretical framework provides a structured way to understand, explain, and predict phenomena, enabling the identification of key elements and fostering insightful analysis (Collins & Stockton. 2018). To address this gap, our study adopts the TOE framework to investigate the drivers influencing I4.0 adoption for enhancing AFSC sustainability.

3. Research methodology

To address the research questions proposed in this study, we employed an exploratory qualitative approach through multiple case studies. A multiple case study approach is well-suited for this research, as it enables a comprehensive exploration of a complex real-world issue with limited prior empirical evidence (McCutcheon & Meredith. 1993). This approach provides robust and compelling evidence, leading to deeper insights and a more thorough understanding of the phenomenon (Barratt et al. 2011). Further, a case study approach enables researchers to gather rich data from multiple sources to achieve data triangulation (Yin. 2018). For example, agri-food industry digitalization reports and I4.0 company websites were checked to validate and complement interview data, offering an external perspective on internally collected information.

3.1 Data collection

Purposive sampling is a widely adopted technique in qualitative research for identifying and selecting information-rich cases relevant to the phenomenon of interest (Palinkas et al. 2015). This study adopted this sampling approach to identify participants aligned with the research objectives. To ensure the selection of suitable participations, three criteria were developed through a roundtable discussion with two professors specializing in digital supply chain management. First, participants were required to have over 10 years of working experience in the agri-food industry, along with a strong understanding of I4.0 technologies and their implementation in the sector. Second, participants needed to be middle- or senior-level management team members, as this study focuses on the drivers of I4.0 adoption for achieving AFSC sustainability. Individuals at these levels are more likely to be knowledgeable about industry trends, company development directions, and actively involved in the company's strategic decision-making. Third, participants had to be directly engaged in the implementation of I4.0 technologies within their companies to provide firsthand insights into the process.

Through our involvement in multiple projects funded by the EU Horizon 2020 Programme and the UK Royal Society and National Natural Science Foundation of China co-funded programme, we have established strong connections with Chinese agri-food industry practitioners. As a result, three Chinese professors specializing in agricultural equipment, policy, and soil water content have committed to disseminating project information within their personal networks and assisting in identifying suitable participants. Leveraging both their networks and our own, we initially identified 37 AFSC practitioners interested in this study. However, not all were invited to the next stage of interviews. Applying our selection criteria, we excluded individuals lacking sufficient experience in the agri-food industry or knowledge of I4.0 adoption in the sector. This refinement process resulted in a final pool of 16 qualified participants. The detailed information about these interviewees is provided in Table 2. Guest et al. (2006) suggested that a minimum of 12 interviews is necessary to achieve data saturation in a qualitative study. Similarly, Braun and Clarke (2006) recommended that a qualitative study employing thematic analysis should include 12 to 20 participants to ensure sufficient data depth and thematic development. Our sample size of 16 AFSC practitioners theoretically suggests that data saturation point maybe reached; however, further evaluation will be conducted to confirm this.

Table 2 Detailed information of interviewees

Case	Interviewee's position	Relevant working experience (Year)
A large farm that responsible for cultivating vegetables	Technology director	10
	Marketing director	12
A vegetable processing company specializes in cleaning, packaging, and canning vegetables to ensure they ae safe, high-quality, and ready for distribution and consumption	Marketing director	15
	Operation director	16
A cold chain logistics company specializes in the storage, transportation, and distribution of temperature-sensitive products, such as vegetables	Senior operation manager	21
	Transportation director	
An agricultural focused higher education institution dedicated to the research and development of intelligent agricultural equipment, which plays a vital role in advancing modern farming technologies	Professor in agricultural equipment	26
	Professor in agricultural facilities	30
A regional agricultural department of government is tasked with formulating and implementing agricultural policies	Head of agricultural technology	14
	Head of agricultural policy	13
An integrated water and fertilizer equipment manufacturer specializes in designing, producing, supplying advanced systems that optimize use of water and fertilizers in agricultural practices	Head of technology department	16
	Head of marketing department	12
A supermarket is responsible for providing consumers with a wide range of fresh, packaged, and household products	Senior marketing manager	15
	Senior stock management manager	13
A non-profit technical and knowledge service is dedicated to disseminating agricultural technology	Knowledge management director	22

knowledge to farmers, agribusiness, and rural communities	Technology management director	24

Two senior PhD students, who were involved in the systematic literature review, were responsible for conducting empirical data collection in China. Their fluency in Chinese, predominant role in this project, and deep understanding of I4.0 and the AFSCs, made them well-suited for this task. Each interview lasted on average of 90 minutes, with some extending beyond 270 minutes. With participants' permission, all interviews were recorded using voice memos on an iPhone 16. After conducting 12 interviews with AFSC practitioners, we observed that "government subsidies" and "knowledge sharing" frequently emerged as recurring themes in interviews with AFSC practitioners. To ensure data saturation, we conducted four additional interviews. Following the completion of 16 interviews, no new themes emerged, confirming that data saturation had been achieved. Consequently, the final sample size for this study was 16 interviews.

3.2 Data analysis

The qualitative data collected through semi-structured interviews were analyzed using thematic analysis, following a five-step process: transcribing, editing, coding, categorizing, and reporting (Zhao et al. 2025). First, we transcribed each digital recording verbatim with the assistance of Otter.ai (https://otter.ai/), an AI-driven speech-to-text transcription software. This process generated 96 pages of transcripts from 16 interviews, averaging six pages per interview. Then, we edited the transcripts by removing irrelevant content, such as general company information and participant introductions. Afterwards, we immersive read these transcripts several times to increase our familiarity, and subsequently code as many as sentences and paragraphs that relevant to the drivers of I4.0 adoption for AFSC sustainability. In the categorization step, codes with similar meanings were grouped under distinct themes, which were then clustered into broader aggregate dimensions. Prior studies such as Hassoun et al. (2023), Rejeb et al. (2024a), and Zhao et al. (2025a) that provide insights into the drivers facilitating I4.0 adoption for a more sustainable agri-food industry, were used as the theoretical foundation to inform this study. Finally, we used the first-order codes, second-order themes, and aggregate dimensions that developed by King and Horrocks (2010) to present our findings.

4. Findings and discussions

In this section, we present our findings and highlight our contributions to both knowledge and managerial practices by comparing our research with previous studies.

4.1 Findings

Table 3 summarizes the key findings of this study, highlighting 15 drivers of I4.0 adoption that contribute to enhancing sustainability in the AFSC. These drivers have been systematically categorized into three dimensions of technological, organizational, and environmental based on the TOE framework.

Table 3 Drivers of I4.0 adoption for enhancing AFSC sustainability

First-order codes	**Second-order themes**	**Aggregate dimensions**
"For example, autonomous driving technology is relatively mature, and environmental monitoring systems are also quite advanced".	High maturity for the widely adopted I4.0 technologies	Technology
"Operational skills need to be continuously updated, as some equipment is constantly being updated and replaced".	Continuous investments to update technologies	
"In addition, it can help prevent underground leakage pollution".	Reducing underground water pollution	Organization
"From the perspective of applying integrated water and fertilizer management system, it is possible to achieve over 70% water savings, thereby enhancing sustainability".	Reducing agricultural water usage	

"Additionally, in terms of precise water and fertilizer management, it is possible to significantly reduce the amount of fertilizer used, leading to substantial savings in fertilizer application".	Reducing fertilizer usage	
"From the perspective of automation applications, there are two main benefits. One is to reduce the workload and labor consumption, thereby potentially improving the working environment. In addition, it focuses on resource competition management to prevent waste. This is a very necessary measure".	Reducing labor consumption and improving working environment	
"The application of technical services and equipment requires an intermediary link. If this link is not adequately established, the promotion of agricultural technology will face significant challenges".	Adequate technical services to disseminate knowledge	
"At this stage, government subsidies are provided to farms".	Government subsidies to farmers and manufacturers	
"…It was initially proposed for application in sales due to the long-standing mutual distrust between sellers and buyers".	Long-standing mutual distrust between sellers and buyers	Environment
"For example, the fertilizer usage for vegetables is as high as 1.5 tons per mu, which is quite alarming. In terms of pure freshwater, the usage can reach 400-500 kilograms, which could be several times higher than in Europe and the United States".	High chemical fertilizer usage	
"…The government introduced an initiative called "streamlined operations" to reduce workers' labour intensity and human resource consumption, thereby improving working environment".	Policy supports to reduce resource consumption	
"From an application perspective, the scaling of agriculture in China is now gradually accelerating".	Promoting of scaling agriculture	
"The agricultural sector has initiated large-scale training programs for new-generation farmers, with a focus on enhancing the quality and skills of growers".	Large-scale skill training for new generation of farmers	
"By establishing platforms, we enable everyone to share information".	Deployment of platforms to widely share information	
"The coverage of public networks and the BDS is completely reliable".	Infrastructures to support I4.0 deployment	

In the technology category, we identified two drivers, including high maturity for the widely adopted I4.0 technologies and continuous investments to update technologies. For example, one interviewee stated: *"In terms of equipment maturity, the current state is quite advanced. We have several brands offering integrated water and fertilizer systems, including pressure tanks and other equipment, which have been well-developed. Locally produced equipment holds a market share of over 95%. In contrast, products from other countries are too expensive and lack mature management experience and operation"*. This highlights why farmers prefer technologies that are already widely deployed and supported by continuous technical and knowledge-based services for maintenance.

In the organizational category, our findings indicate that agri-food organizations adopt I4.0 technologies primarily due to their potential benefits. These include mitigating underground water pollution, reducing labour consumption and improving the working environment, optimizing agricultural water and fertilizer usage, enhancing access to technical knowledge and services, and leveraging government subsidies that incentivize digital transformation in the sector. One interviewee stated: *"From the perspective of using water and fertilizer integrated system, it can achieve over 70% water savings and enhance sustainability. Additionally, it can help prevent underground leakage pollution. This is crucial because large amounts of water and fertilizers entering water bodies may lead to overall groundwater contamination"*. Moreover, our interviewees emphasize the crucial role of non-profit technical and knowledge services, stating: *"Public welfare-oriented agricultural technology extension plays a vital role in I4.0 adoption, particularly in resolving conflicts between manufacturers, farmers, and researchers"*.

In the environmental category, we identified seven drivers of I4.0 adoption for enhancing AFSC sustainability, including long-standing mutual distrust between sellers and buyers, high chemical fertilizer usage, policy supports to reduce resource consumption, promotion of scaling agriculture, large-scale skill training for the new generation of farmers, deployment of platforms to widely share information, and infrastructures to support I4.0 deployment. One interviewee stated: *"I4.0 technologies, such as intelligent greenhouse, IoT, and water and fertilizer integration system, are typically more feasible and cost-effective for large-scale farms exceeding 200 or 300 hectares. This economic and operational reality has driven our country to accelerate the consolidation of farmland into the hands of a smaller number of farmers, enabling them to leverage advanced technologies for improved efficiency, sustainability, and productivity in agriculture"*. Another interviewee highlighted: *"For example, autonomous tractors are relatively mature, and environmental monitoring systems are also widely adopted. These technologies' successful adoption is due to high-speed internet access across rural areas and wide coverage of BDS"*. Our findings further highlight the importance of building various platforms to accelerate information sharing across AFSC practitioners: *"Government and leading enterprises focus on building various platforms, such as traceability, information interconnection, and production-marketing platforms. Once information is shared, it allows for a quicker response in terms of technology application, product sales or processing, market demands, land conditions, and feedback from farmers. This fosters greater efficiency and adaptability across the AFSC"*.

Based on our findings, we developed an "onion" framework with multiple layers that illustrate key aspects of I4.0 adoption for enhancing AFSC sustainability (see Figure 1). These layers include the drivers of I4.0 adoption, the specific technologies implemented on farms, and the primary AFSC stakeholders responsible for accelerating the integration of these technologies.

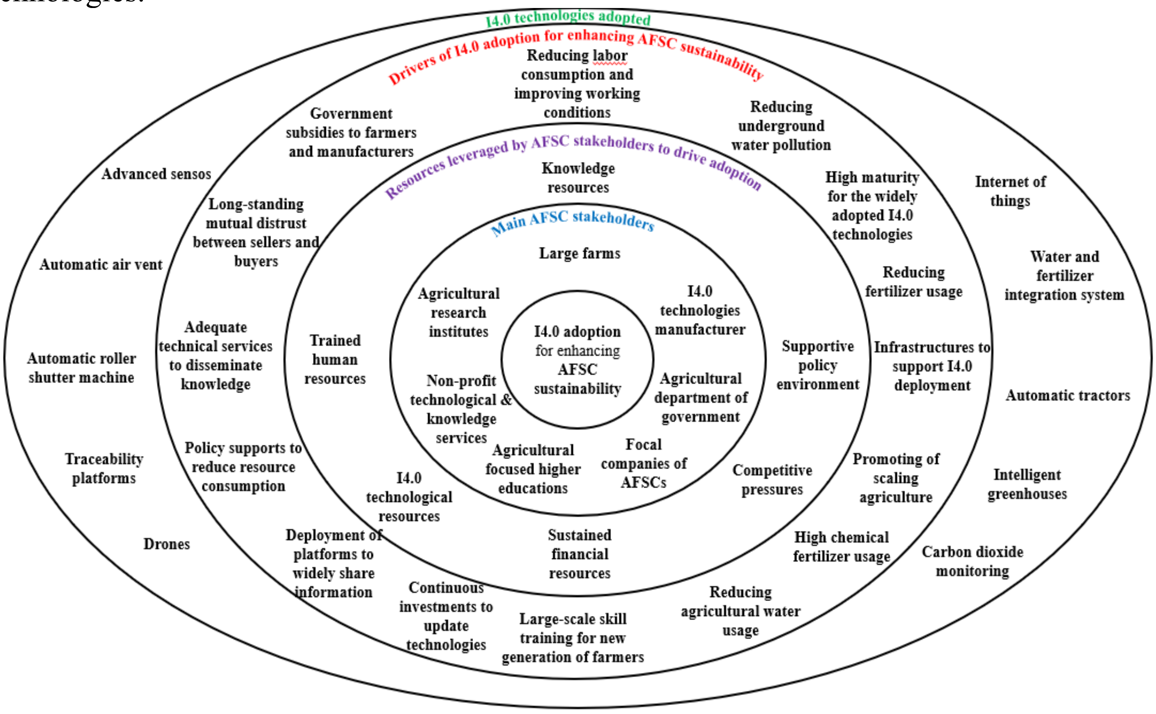

Figure 1 An "onion" framework to illustrate key aspects of I4.0 adoption

4.2 Discussions

Our findings diverge from most existing studies, thereby expanding knowledge on I4.0 adoption and supply chain sustainability. For example, Hmamed et al. (2024) examined the adoption of I4.0 technologies in the textile sector to support a sustainable and circular supply chain. Their study identified organizational practices, environmental pressures, and technological readiness as key drivers of adoption. However, they did not specify detailed factors influencing the process. Our research addresses this gap by providing a nuanced understanding of I4.0 adoption in the agri-food industry. Notable drivers we identified include the long-standing mutual distrust between sellers and buyers, the promotion of scaling agriculture, and large-scale skill training for the new generation of farmers. Similarly, Pandey et al. (2025) outlined 15 enablers for benchmarking I4.0 and supply chain sustainability, including data security and handling, process innovation, and real-time monitoring. However, their study did not explore how to effectively leverage these enablers. Our research extends their work by not only highlighting the drivers but also identifying the resources available, the primary AFSC stakeholders accelerating I4.0 adoption, and the specific technologies being implemented in the agri-food sector. Provensi et al. (2025) emphasized the role of various AFSC stakeholders, such as rural producers, SMEs, consumes, universities, and technology suppliers, in driving agri-tech adoption in supply chains. However, they overlooked the crucial role of government agricultural departments in facilitating I4.0 adoption. Moreover, their study found that AI and big data analytics are widely adopted in Brazilian AFSCs. Our study contributes by revealing that in China, advanced technologies like AI, big data analytics, blockchain, and robotics are seldom adopted due to their significant impact on increasing costs of terminal logistics. Instead, the most widely adopted I4.0 technologies in China's agri-food industry include advanced sensors, automatic air vents, automatic roller shutter machines, traceability platforms, drones, IoT systems, water and fertilizer integration systems, automated tractors, intelligent greenhouses, and carbo dioxide monitoring systems. Finally, Bag et al. (2023) argued that South African manufacturers adopt I4.0 technologies to improve resource consumption rate and reduce waste and pollution. Our study supports their findings, confirming that AFSC stakeholders adopt I4.0 technologies to reduce underground water pollution, agricultural water and fertilizer usage, and labour consumption. As such, our study makes a contextual contribution, extending the work of Bag et al. (2023), by identifying similar behaviours within a radically different geographical context.

The role of the TOE framework in the adoption of technological innovations is well-documented in the literature. For example, Govindan (2023) applied the TOE framework to explore success factors influencing the digital transformation of the traditional circular economy, Raj and Jeyaraj (2023) conducted a meta-analysis to summarize the key antecedents of I4.0 adoption, and Mishra and Pathak (2024) extended the TOE framework to identify enablers shaping the adoption and integration of I4.0 technologies in human resource management. Existing studies primarily use the TOE framework to analyze factors influencing I4.0 adoptions for enhancing supply chain sustainability, focusing on technological, organizational, and environment factors affecting I4.0 technologies adoptions. However, they often overlook the crucial connections between resources, industry stakeholders, and the specific I4.0 technologies being adopted. Our study extends this discourse by demonstrating that I4.0 adoption in the agri-food industry is a multidisciplinary effort requiring the mobilization of knowledge, policy, financial, technological, and human resources across the AFSCs.

This study offers valuable insights for government agricultural departments and technology and knowledge service providers. First, government subsidies play a crucial role in promoting the adoption of I4.0 technologies in the agri-food industry. However, our participants criticized the current subsidy model, which primarily supports farmers who have already adopted I4.0 technologies rather than manufacturers producing these technologies. To facilitate the widespread adoption of I4.0 solutions, the Chinese government should consider shifting its subsidy strategy to support I4.0 technology manufacturers, enabling them to scale production, reduce costs, and make these technologies more accessible to farmers. Second, our participants emphasized the crucial role of non-profit technological and knowledge services in facilitating the adoption of I4.0 technologies, particularly in resolving conflicts between manufacturers, agricultural research institutes, and farmers. However, the current provision of these services is primarily government-led, which limits their effectiveness in disseminating I4.0-related knowledge and support. To enhance the adoption of I4.0 technologies, independent non-profit technological and knowledge service organizations should be established and expanded across rural areas in China, ensuring broader access to expertise and fostering collaboration among key stakeholders.

5. Conclusions, limitations and future research directions

Our study was inspired by China's exceptionally high agricultural mechanization rate and its sustained improvements in agricultural sustainability over recent years. Grounded in the TOE framework, we investigated the drivers of I4.0 adoption for enhancing AFSC sustainability using data from interviews with 16 AFSC practitioners and analyzing through thematic analysis. Our findings reveal that the successful deployment of I4.0 technologies to achieve AFSC sustainability relies on multidisciplinary collaboration and the collective efforts of multiple stakeholders, including farmers, I4.0 technology manufacturers, government agricultural departments, agricultural research institutes, agriculture-focused higher education institutions, non-profit technological and knowledge service providers, and focal AFSC companies. These stakeholders collaboratively mobilize policy, financial, knowledge, technological, and human resources, effectively leveraging various drivers to accelerate I4.0 adoption.

We acknowledge this study has marginal limitations, which can be addressed through future research. First, this study employs a qualitative approach to gain an in-depth understanding of the drivers of I4.0 adoption for enhancing AFSC sustainability. While qualitative research provides rich insights, it is often criticized for lacking statistical rigor (Gioia et al. 2012). Future research could address this limitation by adopting a mixed-method approach, incorporating multi-criteria decision-making techniques to quantitatively assess and prioritize the identified drivers. For example, total interpretive structural modelling (TISM) could be employed to explore the interrelationships among the drivers by structuring them into different layers of a hierarchical framework (Zhao et al. 2024c), while a group-based fuzzy analytic hierarchy process (GFAHP) could be used to rank the drivers by integrating multiple experts' opinions (Zhao et al. 2024d). Second, the generalizability of our findings is limited, as data were collected solely from China. Future studies could test and refine the proposed "onion" framework in different geographical contexts to enhance its applicability and validate its relevance across diverse socio-economic and regulatory environments.

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