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Research article

Deployment of Industry 4.0 technologies to achieve a circular economy in agri-food supply chains: A thorough analysis of enablers

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ABSTRACT

With the global population projected to reach 9.7 billion by 2050, pressure on global natural resources will increase by 50–90%, exceeding planetary boundaries. Industry 4.0 (I4.0) technologies are widely considered feasible for resolving the conflict between population growth and natural resources. However, their adoption by the agri-food industry has been slower than in manufacturing and automotives. Their fragmented, non-comprehensive, and atheoretical nature of scholarly research relating to I4.0 and the circular economy (CE) impede practitioners' deeper understanding. Grounded in grand theory, we analyze enablers of I4.0 deployment to achieve CE in agri-food supply chains (AFSCs). We thematically analyze data collected from 32 Chinese AFSC practitioners through semi-structured interviews to identify 27 enablers. We then implement a group-based fuzzy analytic hierarchy process (GFAHP) to prioritize these enablers based on the opinions of 10 decision makers. Our results differ from most existing studies. First, we find that AFSCs' successful deployment of I4.0-enabled CE depends on the collective efforts of environmental factors, supply chains, organizations, and individuals. China's hierarchical cultural value orientation is the "lubricant" linking these factors to achieve synergies. Second, our prioritization results show that success depends heavily on environmental factors and organizations, and relatively little on supply chains and individuals. Enablers such as willingness to learn new knowledge, knowledge of I4.0 and CE, rural revitalization policy, new infrastructure construction policy, and enhanced digital skills are prioritized amongst the 27 identified enablers. This study has limitations, such as generalizability, that should be addressed in future research.

1. Introduction

We all need fresh air to breathe, clean water to drink, healthy food to eat, and hospitable climate patterns (UNIDO, 2024). However, human impacts from overpopulation, pollution, burning fossil fuels, and deforestation are pushing the boundaries of what our planet can provide. Agri-food systems are central to human activities. For example, over 70% of earth's land surface and 67% of marine environments have been significantly altered by human agricultural activity; the agricultural sector contributes approximately 30% of greenhouse gas emissions; agribusiness is responsible for 80% of deforestation; more than 40% of freshwater resources are used for 20% of irrigated agriculture; and our agri-food system is a major driver of biodiversity loss, placing more than 24,000 species (86%) at risk of extinction (UNEP, 2021a). Between 2030 and 2050, unless technological innovations and dedicated mitigation measures are implemented, factors such as population growth, higher income levels, more complex food requirements, and increased calory consumption are expected to increase the agri-food system's environmental effects by 50–90%, thus reaching planetary boundaries for freshwater use, land use, and ocean acidification (Springmann et al., 2018; Zhao et al., 2024c). Moreover, it is estimated that by 2050 the global agri-food system will need to produce 70% more food to satisfy the approximately 10 billion population (World Bank, 2022). However, given current rates of resource depletion, soil erosion, species extinction, and ecosystem pollution, existing agri-food systems are unsustainable (Olson, 2023) for several reasons. First, conventional

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agricultural systems are intensive, relying on agrichemicals to maximize agricultural production. Such practices include high irrigation rates, mono-cropping, and limited recycling (Sumberg and Giller, 2022). Second, the current linear food consumption model will exceed environmental limits within which humanity can safely operate. For example, approximately 931 million tonnes of food are wasted by households, retail supermarkets, and the food service industry every year (UNEP, 2021b; Zhao et al., 2023). This accounts for 40% of all food produced worldwide, and is even higher than the 30–33% previously estimated (EIT Food, 2021). Third, stakeholders in agri-food systems, including producers, retailers, learning institutions, and financial institutes, all have the potential to play unique roles in changing this situation, but are not doing so. To align with the United Nations' Sustainable Development Goals (SDGs) and the Paris Agreement, the Food and Agriculture Organization (FAO, 2024) has called for the building of a sustainable and circular agri-food system to avoid food waste and loss, reduce the likelihood of spoilage, keep products and materials in use, and regenerate natural systems.

Three widely-accepted principles for building circular food systems to benefit people, organizations, and the environment are eliminating waste and pollution, circular use of products and materials (at their highest value), and regenerating nature (Ellen Macarthur Foundation, 2024). To achieve a circular economy (CE) for agri-food systems, emerging Industry 4.0 (I4.0) technologies are key to improving efficiency and visibility across agri-food supply chains (AFSCs). AFSCs link activities from farm to fork, involving all stages of production, processing, wholesaling, distribution, and consumption (Gokarn and Choudhary, 2021). Potential uses of I4.0 technologies include autonomous drones and satellite imaging to monitor land and predict areas at risk of deforestation; artificial intelligence (AI) to design waste-free economies for food; robotics combined with machine learning to reduce chemical and water resource inputs and accelerate regenerative agriculture; blockchain technology to enhance AFSC transparency and reduce imbalance between supply and demand, thereby minimizing food loss; and 3D printing to help create a closed-loop manufacturing process by introducing new materials for repurposing waste. Supply chain data platforms can be built to develop a unified view of the overall supply chain (Despeisse et al., 2017; Wang et al., 2020; Ciccullo et al., 2021).

Although I4.0 technologies promise significant benefits for developing CE in AFSCs, they require certain conditions to reach their full potential. In particular, building a circular AFSC is a system challenge necessitating actions by individuals, research institutions, food businesses, governments, and even society at large. For example, the European Environment Agency (2021) highlights that transitioning successfully to CE depends heavily on synergies between five crucial dimensions: culture and mindset, technological requirements, dedicated infrastructure, economic viability and market enablement, and regulatory environment. More specifically, enabling conditions such as high I4.0-technology readiness, broadband access, safe data exchange, and knowledge of how to apply I4.0 technologies are considered important prerequisites for I4.0-enabled CE. However, consideration of legal, social, political, and natural environmental perspectives on enabling conditions is lacking. Tripathy et al. (2023) identify 13 economic, social, and environmental enablers facilitating the transition to recycling lithium-ion batteries. These include carbon dioxide emissions reduction, employment opportunity creation, and availability of reliable technology. However, they fail to investigate legal, political, technological, social, and individual enablers in any depth. Khan et al. (2022) list enablers of I4.0 for CE from internal and external perspectives, but their taxonomy is very broad, limiting its use. Despite a vast literature on the drivers, enablers, critical success factors, and facilitators of CE implementation in I4.0 (Luthra et al., 2020; Behl et al., 2023; Zhang et al., 2023), its atheoretical, incomplete, and unscientific taxonomy and lack of context specificity to I4.0 for CE limit the insights and advances to be gained. Moreover, although scholarly interest in the relationship between I4.0 and CE is increasing, most such work is theoretical or case study-based (Felsberger and Reiner, 2020; Rosa et al., 2020; Awan et al., 2021). The lack of empirical studies adopting individual, organization, supply chain, and environmental perspectives impedes industry-wide adoption of I4.0 (Remero et al., 2021).

To address these research gaps and accelerate deployment of I4.0 technologies to build a more efficient, sustainable, resource-conscious agri-food industry, we conducted a thorough analysis of enablers of I4.0 technology deployment to achieve CE in AFSCs through the theoretical lens of grand theory (GT). GT is suited to understanding cause-and-effect relationships within social phenomena by linking micro, meso, and macro levels of reality. We sought to answer two research questions: what enablers might facilitate AFSCs' transition towards CE in the context of I4.0; and how should these enablers be prioritized? The first aims to identify various enablers that may facilitate deployment of I4.0 technologies to achieve CE of AFSCs. As AFSCs are multi-level frameworks that include individuals and organizations, and both are affected by their external environments, we identify enablers at individual, organizational, supply chain, and environment levels. To answer the first research question, we conducted interviews with 32 Chinese AFSC practitioners, and used thematic analysis to identify 27 enablers. China was selected as a context because it has been an early adopter of technology facilitating the transition to CE, and a leading developer of legislative packages explicitly targeting CE (Circular, 2022). For example, in its 14th Five Year Plan from 2021 to 2025, it has set clear numerical targets such as utilizing 60 million tons of wastepaper and 320 million tons of scrap steel, and producing 20 million tons of recycled non-ferrous metals (Circular Innovation Lab, 2023). The second research question aims to prioritize the identified enablers to understand their relative importance. This is critical given agri-food organizations' limited budgets and scarce resources. Clear consideration of key I4.0 adoption enablers will reduce AFSC practitioners' time and effort in deploying I4.0 technologies to achieve CE. To answer the second question, we employed a group-based fuzzy analytic hierarchy process (GFAHP) to prioritize our 27 enablers based on the judgements of ten experts. GFAHP can provide more precise results by including multiple decision makers, and is considered more realistic for tackling real-life decision-making problems (Zhao et al., 2024c).

This study contributes significantly to knowledge and managerial practices. With regard to the former, first, our results indicate that successful deployment of I4.0 technologies to achieve CE in AFSCs depends on collective efforts at the macro level of environments, the meso levels of supply chains and organizations, and the micro level of practitioners. China's hierarchical cultural value orientation is the "lubricant" linking individuals, organizations, and AFSCs to achieve synergies. Second, we identify 27 enablers that may contribute to I4.0 technology deployment, the majority of which have not previously been recognized. Third, this study appears to be the first to implement a GFAHP by seeking the opinions of decision makers to categorize and rank enablers. Our contributions to managerial practices include our recommendations that governments should create appropriate political, economic, social, technological, environmental, and legal (PESTEL) environments to facilitate I4.0 technology adoption, that AFSC managers should strengthen knowledge mobilization (KMob) through more practical-based lectures, and that the control interfaces of I4.0-enabled agricultural technologies should be simplified.

In the remainder of this article, in Section 2 we review literature relevant to I4.0, CE, and supply chains to build a theoretical framework and identify research gaps. In Section 3 we describe our research methodology and justify our data collection and analysis methods. In Section 4, we explain how we collected data in China. In Section 5 we present the results of our identification and prioritization of enablers. In Section 6 we discuss our unique contributions to theory and managerial practices, and in Section 7 we draw some conclusions.

2. Literature review

In this section we describe our theoretical framework and explain China's agricultural context. We then review relevant literature on supply chains, I4.0, and CE, and identify research gaps.

2.1. *Grand theory*

GT is often used to explain large social landscapes by linking micro-, meso- and macro-levels of reality (Favell, 2023). It aims to reveal cause-and-effect relationships that can be broadly applied to all similar cases and contexts of the phenomenon of interest (Reeve, 2016). For example, utilizing GT to develop an understanding of European Union (EU) differentiation, Schimmelfennig and Winzen (2019) conclude that wealth, identity, state powers, and pre-existing differentiation are important drivers. Zhao et al. (2024b), who adopt a GT lens to develop a multi-level resilience framework, find that supply chain resilience is determined by resilience factors relating to macro-level environments, meso-level organizations, and micro-level individuals. Grounded in GT, Zhao et al. (2024c) identify and prioritize barriers to adopting I4.0 to achieve AFSC sustainability. Our study is guided by GT for several reasons. First, existing studies focusing on AFSCs' achievement of CE through I4.0 technology deployment are highly specialized. For example, Belaud et al. (2019) propose a big data framework for agri-food 4.0; Kumar et al. (2021) identify 11 barriers to I4.0 adoption to achieve CE; and Abbate et al. (2023) highlight driving forces and key technologies that might facilitate the agri-food sector's sustainable transition. However, this specialist work lacks broader consideration of explanatory mechanisms. Second, although various theories have been used to develop insights into the topic, such as the resource-based view (RBV) and knowledge-based view, and social network, boundary-spanning, and social embeddedness theories (De Sousa Jabbour et al., 2023; Despoudi et al., 2023), using GT would extend understanding of this topic. Third, we believe that AFSCs' deployment of I4.0 to achieve CE is a social phenomenon involving engagement at the environmental, supply chain, organizational, and practitioner levels. Failure to encompass all four levels will result in incomplete understanding. For example, Mehmood et al. (2021) review the literature on drivers of AFSCs toward CE, but their summary focuses mainly on the environmental perspective (e.g., financial, health, and social benefits). Similarly, Yontar (2023) highlights 12 drivers originating from PESTEL environments that may facilitate I4.0 deployment to achieve circular AFSCs. However, her study neglects drivers originating from supply chains, organizations, and individuals. Thus, our study complements existing studies by using GT to gain a comprehensive understanding of the topic (see Fig. 1).

We believe that AFSCs' deployment of I4.0 to achieve CE is determined by forces originating from PESTEL environments, supply chains, organizations, and individuals. External PESTEL environments impact on individuals' behaviours and decisions, and the latter influence organizational decision making in applying I4.0 to achieve CE.

2.2. *China's unique agricultural context*

China's agricultural context has several unique characteristics. First, its farmland is characterized by scattered, small-scale farms, impeding agricultural industrialization and mechanization. World-wide, 72% of farms have less than 1 ha of farmland, with 69% in Japan, whereas approximately 90% of American farmers have over 5 ha of farmland. In China, 93% of farmers have less than 1 ha. Small-scale agricultural production, low levels of industrialization, and low-quality agricultural products seriously affect China's agricultural efficiency and competitiveness (EqualOcean Intelligence, 2021). Moreover, excessive use of agrichemical products and pesticides has reduced the quality of its farmland. For example, average pesticide usage per hectare is 10.3 kg in China, compared with 2.2 kg in the USA and 3.0 kg in the UK. A second

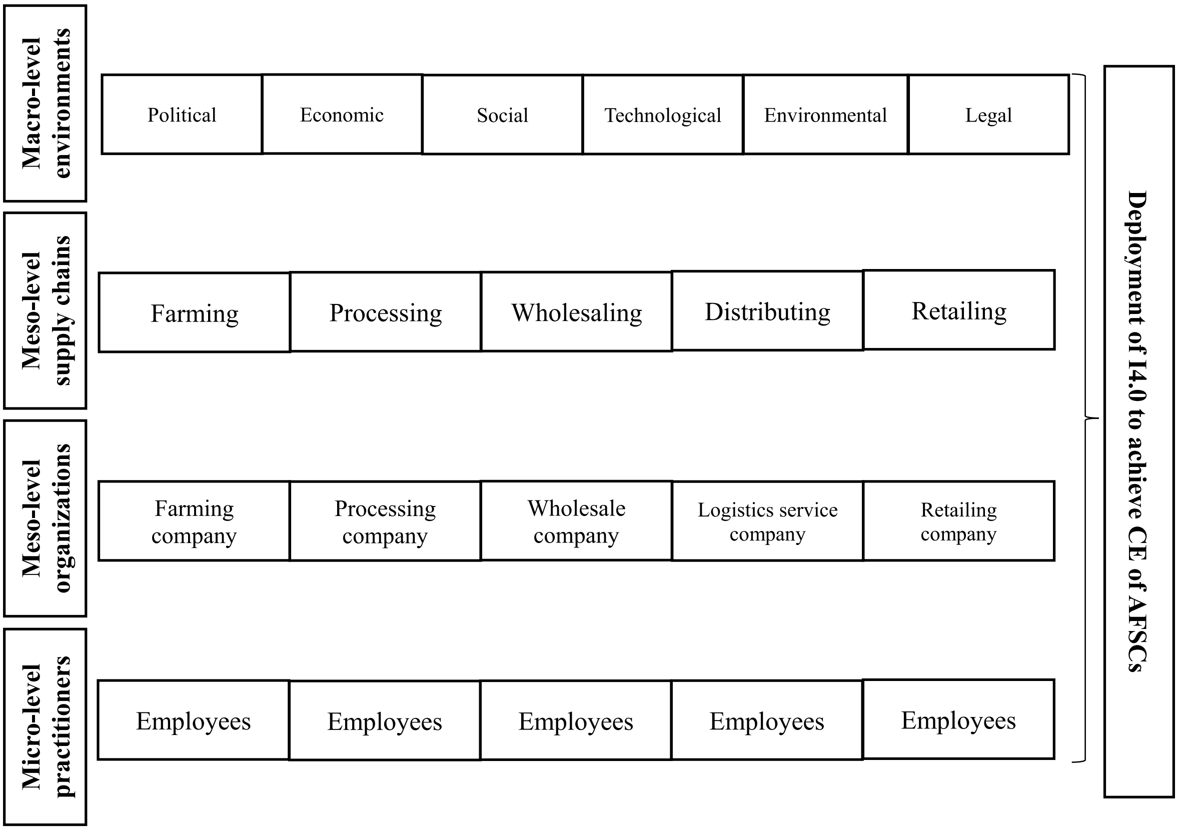

Fig. 1. A "grand" theoretical framework.

key characteristic is that, from 2015 to 2020, a large proportion of the government's agricultural funding was allocated to cultivating and processing companies, whereas policymakers have devoted much less attention to other stages of AFSCs responsible for agricultural KMob, agri-tech services, agri-food trading, and research and development. For example, 1586 agri-food cultivation and processing companies received government funding between 2015 and 2020, compared with only 101 agri-food service and technological companies. These imbalanced allocations have skewed the structure of China's agricultural industry and influenced the development of agricultural technology (CAICT and CARD, 2021). Third, China's AFSCs are characteristically long, complex, and involve many stakeholders across pre-, mid-, and post-production stages, making it difficult to monitor agri-food products and causing frequent food safety issues (OECD, 2018). Fourth, to satisfy consumers' diverse food preferences, China imports many agri-food products (e.g., sugar, vegetables, fruit, and livestock), giving rise to food security issues (Jiang, 2020). Fifth, climate change is causing frequent natural disasters that seriously affect agricultural productivity, including droughts, floods, and snowstorms. For example, the 2021 Henan floods reduced yields from 148,100 ha of farmland by more than 70%, and yields from 457,400 ha of farmland by more than 30% (Chen, 2021). Finally, China's aging population and massive urbanization have reduced younger generations' willingness to work in the agri-food industry, especially in rural areas.

In the face of increasing challenges posed by business uncertainties, social changes, and external environments, scholars, practitioners, and policymakers believe that integrating I4.0 technologies to achieve smart AFSCs is a feasible way to adapt to climate change, increase farm's profitability, reduce greenhouse gas emissions, and thus minimize waste and maximize environmental protection (Sharma et al., 2022).

2.3. I4.0 technologies and CE

I4.0, referring to the fourth industrial revolution, was introduced in 2011 at the Hanover Fair in Germany (Oliveri et al., 2023). It connects various advanced information and communication technologies (ICTs), and is widely deployed in industry to build intelligent networks of machines and industrial processes (Zhang et al., 2021). I4.0 aims to seamlessly link humans, machines, and manufacturing processes by providing real-time information flows to facilitate coordination, cooperation, and collaboration between different stages of production processes and consumers' requirements. The ultimate goals are to maximize production efficiency, minimize production costs, and satisfy individuals' needs for products and services (Rosa et al., 2020; Kim et al., 2023). Despite diverse scholarly research on I4.0, consensus has not been reached on which technologies should be categorized as such. Having examined recent literature reviews and checked for I4.0 design principles such as decentralization, real-time, service-orientation, modularity, interoperability, and virtualization, we focused on ten I4.0 technologies: cyber-physical systems, internet of things (IoT), big data analytics (BDA), cloud technology, artificial intelligence, blockchain, simulation, augmented/virtual reality (AR/VR), industrial robots, and additive manufacturing (Oztemel and Gursev, 2020; Zheng et al., 2021; Lemstra and De Mesquita, 2023). I4.0 promises a range of benefits and potential applications in a broad range of fields, attracting the attention of scholars, practitioners, and policymakers. For example, it enables supply chain integration, digitalization, and automation, thereby contributing to extensive supply chain information sharing and performance improvement (Fatorachian and Kazemi, 2021). BDA and its applications are widely used to support clinical decision making, optimize clinical operations, and reduce healthcare costs (Fanelli et al., 2023). Autonomous robots such as tractors, harvesters, and picking and packaging systems are being deployed to enhance agricultural productivity (Yang et al., 2023).

As implementation of the 2030 agenda and the United Nations' SDGs accelerates, I4.0 also has great potential to enable and implement CE. CE is a model of production and consumption involving sharing, leasing, reusing, repairing, refurbishing, and recycling existing materials and products as much as possible (European Parliament, 2023). It aims to extend product lifecycles and minimize waste, and thereby create further value (Balsalobre-Lorente and Shah, 2024). Existing studies in this domain fall into two main clusters. The first investigates relationships between CE and I4.0, and focuses on eight key subtopics: digital transformation, lifecycle management, resource efficiency, disassembling and reusing 4.0, recycling 4.0, remanufacturing 4.0, circular business models and smart services, and supply chain management (Awan et al., 2021; Massaro et al., 2021; Jugend et al., 2024; Tiwari et al., 2024). For example, Rosa et al.'s (2020) review of 158 articles concerning circular I4.0 and digital CE reveals that I4.0 is an enabler of CE and may have positive effects on product lifecycle management, but not vice versa. Similarly, Yu et al. (2022) highlight that I4.0 facilitates implementation of CE practices. Joint adoption of I4.0 and CE may have a synergetic effect on businesses' economic, environmental, social, and operational performance (De Sousa Jabbour et al., 2022). Research in the second cluster analyzes challenges to implementing CE in the context of I4.0 (Trevisan et al., 2023). This cluster has received considerable scholarly attention owing to the barriers impeding this transition. For example, Rajput and Singh (2019) list 15 barriers, including investment costs and infrastructure standardization. Kumar et al. (2021) identify and prioritize 11 barriers, amongst which government support and incentives are key. Abdul-Hamid et al. (2024), who analyze 27 barriers, confirm that financial constraints and lack of a collaborative I4.0 CE model are the two key barriers.

Despite rich academic discourses on I4.0 and CE, the narrative and limited scope of analysis impedes deeper understanding of how I4.0 technologies contribute to CE. For example, studies analyze the impact of I4.0 technologies on CE from a single I4.0 technology perspective (Tseng et al., 2018), or examine limited aspects of enablers and barriers facilitating or impeding CE in the context of I4.0 (Shayganmehr et al., 2021). This lack of a holistic understanding may slow the process of CE adoption and pose challenges to achieving the 2030 agenda for sustainable development (UN, 2024). Thus, a comprehensive understanding of enablers of CE through I4.0 deployment is needed.

2.4. Enablers of supply chain CE through I4.0 technology deployment

In this section, we present a systematic review of literature relevant to CE, I4.0, supply chains, and enablers. We drew keywords from existing literature reviews, including Awan et al.'s (2021) review of I4.0 and CE, Gebhardt et al.'s (2022) study of I4.0 and circular supply chains, Mehmood et al.'s (2021) examination of CE in AFSCs, and Lu et al.'s (2024) work on I4.0 and CE for sustainable supply chain management (SSCM). We then combined these keywords and used them as search strings in Web of Science and Business Source Complete: ((“drivers” OR “enablers” OR “critical success factors”) AND (“industry 4.0” OR “digital technologies” OR “autonomous” OR “Smart”) AND (“circular economy” OR “closed-loop”) AND (“supply chains” OR “supply management” OR “supply chain management” OR “production management” OR “operations management”)). To ensure quality, we only considered papers published in journals ranked 3, 4, or 4* in the *Academic Journal Guide 2021*. Therefore, we excluded papers published in the *Journal of Cleaner Production*, *International Journal of Information Management*, *Resources, Conservation and Recycling*, *Computers & Industrial Engineering*, *Sustainability*, and *Industrial Management & Data Systems*. To further limit the number of papers, we also stipulated that: (1) the selected studies should clearly focus on identifying enablers of digital circular supply chains, meaning that papers focusing on barriers (or challenges) and assessing relationships between CE, I4.0, and supply chain attributes were excluded; and (2) the studies should be empirical, contributing new knowledge to this area, so theoretical and conceptual papers were excluded. As a result, we identified 10 studies fulfilling our requirements. We then analyzed these papers by summarizing their features, such as the industry focus, theory adopted, and multi-criteria decision-making (MCDM) techniques used (see Table 1).

Amongst various understandings of supply chain CE enablement through I4.0 technology deployment. Yadav et al. (2020) identify 29 I4.0 enablers that may facilitate sustainable manufacturing supply chains, and split these into five categories: informational and technological, environmental, managerial and economic, supply chain management, and organizational and social. Enablers rarely mentioned by other scholars include suppliers' commitment to sustainable procurement, educating customers on sustainability, small budget allocations, and promoting knowledge management (KM) across supply chains. Govindan (2023) identifies 22 success factors on technological, organizational, and environmental dimensions that can be applied to digital transformation of traditional CE. His study differs from others in documenting factors particularly relevant to the textiles industry, including production and consumption of natural fibres, sustainable textile trades, and market-competitive recycled fibres. Behl et al. (2023) propose a sustainable operations framework comprising 15 enablers of I4.0 and CE. Some notable enablers are management participation, horizontal and vertical integration, product lifecycle management, and waste reduction. Luthra et al.'s (2020) analysis of cause effect relationships between different I4.0 and CE drivers reveals that collaboration and transparency among supply chain stakeholders, management support and effective governance, and development of ICT facilities are key causes, whereas competitiveness, waste reduction and efficiency improvement, and adoption of innovative business models are key effects.

2.5. Research gaps

Our meticulous review of previous research on I4.0 and CE in supply chains reveals several research gaps.

First, previous studies have contributed to understanding enablers of I4.0 technology deployment to achieve supply chain CE, but all have analyzed limited aspects of this issue (Shayganmehr et al., 2021). For example, Behl et al. (2023) assess this problem using the five criteria of service and policy framework, industrial ecosystem, man-machine interaction, waste prevention, and smart infrastructure and equipment. Despoudi et al. (2023) categorize enablers into financial, regulatory, cultural, and internal groups, and Govindan (2023) uses technological, organizational, and environmental categories. Our study complements previous studies by identifying enablers from macro-level environments, meso-level supply chains, meso-level organizations, and micro-level practitioners.

Second, among the various MCDM methods used to analyze enablers, the best-worst method (BWM), the fuzzy analytic hierarchy process (FAHP), decision making trial and evolution laboratory (DEMATEL), and fuzzy-DEMATEL are frequently applied to prioritize and build relationships between them (see Table 1). In particular, DEMATEL and its relevant applications are widely used because scholars assume a cause effect relationship between I4.0 and CE (Luthra et al., 2020; Moktadir et al., 2020; Govindan, 2023; Khanzode et al., 2023; Kumar et al., 2023; Zhang et al., 2023). However, these techniques are based mainly on feedback from a single decision maker, which may produce biased or imprecise results. For example, Govindan (2023) determines the most and least desirable enablers from the opinions of one decision maker. Our study differs from previous studies in using GFAHP to prioritize enablers based on the opinions of ten decision makers.

Third, research on I4.0, CE, and supply chains has been conducted in various research contexts, including India's manufacturing, textile, and automobile industries, China's smart industry, Turkey's transport and logistics service industry, and Bangladesh's leather industry (see Table 1). However, China's agri-food industry seems to have received little scholarly attention, as confirmed by several literature reviews on CE and I4.0. For example, based on analysis of 58 articles published between 2009 and 2019, Mehmood et al. (2021) conclude that 29% (n = 17) focus on the automobile industry, and 24% (n = 14) on manufacturing, but only 17% (n = 10) focus on the agri-food industry. Agrawal et al. (2022) find that of the 165 papers selected for analysis, only 34 were authored by academics from Chinese institutions. Assuming that the number of studies focusing on China will be significantly fewer, our study of China's agri-food industry fills this gap.

Finally, although several potential theories are identified, such as RBV, critical success factors (CSF), and technology, organization, and

Table 1
Studies relevant to CE, I4.0, supply chains, and enablers.

Author(s) (year)	Topic focus	Industry focus	Theory used	Research methodology adopted	MCDM techniques	Country focus
Luthra et al. (2020)	Drivers of I4.0 and sustainability	Manufacturing	N/A	Modelling	Grey-DEMATEL	India
Moktadir et al. (2020)	Critical success factors for I4.0 and CE	Leather	N/A	Modelling and case study	BWM and DEMATEL	Bangladesh
Yadav et al. (2020)	A framework to achieve CE using I4.0	Manufacturing	N/A	Modelling and case study	Robust-BWM	India
Behl et al. (2023)	Analysis of I4.0 and CE enablers	N/A	N/A	Modelling	Delphi, FAHP, and F-CoCoSo	N/A
Despoudi et al. (2023)	Enablers of I4.0 and CE in emerging markets	Agri-food	RBV	Interview and modelling	Hierarchical cluster analysis	India
Govindan (2023)	Enablers of digital CE	Textiles	CSF and TOE	Modelling and case study	BWM and Grey-DEMATEL	India
Kazancoglu et al. (2023)	Framework for SSCM to overcome risks in transitioning to CE through I4.0	Transport and logistics service	N/A	Modelling and case study	FAHP and TODIM	Turkey
Khanzode et al. (2023)	Modelling interactions between selected enablers of I4.0 and CE	Manufacturing	N/A	Modelling and case study	DEMATEL	India
Kumar et al. (2023)	Identification and prioritization of critical success factors for implementing I4.0 integrated circular supply chains	Automobiles	N/A	Modelling and case study	Fuzzy DEMATEL	India
Zhang et al. (2023)	Analysis of drivers of I4.0-enabled CE	Smart	N/A	Modelling and interviews	Fuzzy DEMATEL	China
Ali et al. (2024)	Analysis of I4.0-driven CE practices	Textiles	N/A	Modelling and case study	Fuzzy Delphi, BWM, full consistency method, CoCoSo	India
Zhao et al. (2024a)	Understanding the drivers of I4.0 to enhance supply chain sustainability	Agri-food	Middle-range theory	Interviews and modelling	Fuzzy AHP, fuzzy total interpretive structural modelling, and fuzzy MICMAC	China

environment (TOE) framework (see Table 1), previous studies tend to lack theorization, which reduces opportunities to deepen understanding of the topic. Our study fills this gap by applying GT systematically to analyze enablers at the levels of environments, supply chains, organizations, and practitioners.

3. Research methodology

We adopted a mixed-method approach to analyze enablers of I4.0 technology deployment to achieve CE in AFSCs. Mixed methods can generate deeper insights into a phenomenon or address research questions more comprehensively than either quantitative or qualitative methods alone, enable triangulation of both qualitative and quantitative data, and enrich the results with different perspectives on an issue (Tashakkori and Teddlie, 1998; Creswell and Plano Clark, 2011). Several previous studies focusing on deployment of I4.0 to achieve CE have used a mixed-method approach, providing us with some confidence to apply it in this study. For example, Zhao et al. (2024a) adopted a mixed-method approach to understand the drivers of I4.0 deployment to enhance AFSC sustainability. They employed qualitative methods such as semi-structured interviews to collect data, thematic analysis to identify enablers, and quantitative techniques such as fuzzy-AHP-TISM-MICMAC to prioritize the identified enablers. Ali et al. (2024) used questionnaires to collect data and three different MCDM techniques to prioritize I4.0-driven CE practices, and developed a case study to evaluate their results. Zhang et al. (2023) used semi-structured interviews and thematic analysis to identify 11 drivers of I4.0-enabled smart waste management, and then applied a fuzzy-DEMATEL to explore interrelationships among those drivers. Thus, we followed previous studies in adopting a mixed-method approach. Our qualitative methods were semi-structured interviews to collect data from experienced Chinese AFSC practitioners, followed by thematic analysis to identify enablers. We then used the quantitative research technique of GFAHP to prioritize these enablers (see Fig. 2).

3.1. Data collection method

Semi-structured interviews are a qualitative research method in which pre-determined, open-ended questions are asked to gain valuable insights into a particular theme (Dicicco-Bloom and Crabtree, 2006). They have several advantages over other research methods such as questionnaires and structured and unstructured interviews. First, open-ended questions provide more opportunities for both interviewee and interviewer to discuss a particular theme, thereby uncovering unforeseen information and knowledge (Saunders et al., 2015). Unlike most previous studies, we adopted GT to analyze enablers across four levels (environments, supply chains, organizations, and individuals). Second, semi-structured interviews have been widely used to uncover determinants and factors, providing us with some confidence in using them to identify enablers in our study. For example, Jayawickrama et al. (2016) used them to identify determinants of a KM lifecycle, and Zhao et al. (2020) to uncover AFSC risks. Finally, semi-structured interviews are associated with high response rates, enabling researchers to explore complex and sensitive issues, and elicit valuable and more extensive information (Barriball and While, 1994). Thus, we used them to collect data from experienced AFSC practitioners in China.

3.2. Data analysis methods

We analyzed our empirical data collected through semi-structured interviews using a combination of two methods: thematic analysis and GFAHP. Thematic analysis is a qualitative data analysis method widely used to analyze, identify, describe, organize, and report themes found within a dataset (Braun and Clarke, 2006). We adopted it because it is characterized by high flexibility, simplicity, and tangibility across analysis phases (Nowell et al., 2017), and because the results are easily understood by members of the public with low educational levels. Our research context was particularly suited to thematic analysis because only around 55.4% of Chinese AFSC practitioners are educated to junior high-school level, and only 12.2% have a college degree (Zhao, 2022). Other qualitative data analysis methods, such as discourse analysis, do not provide tangible answers to problems, and narrative analysis captures a limited number of answers to research questions, making these inapplicable in our study. Finally, thematic analysis is useful for summarizing key features of a large dataset, highlighting similarities and differences between research participants, and generating valuable insights (Saunders et al., 2015). Thus, we used this method to identify our enablers.

These enablers were then used as inputs into a GFAHP, which we adopted for several reasons. First, reliably addressing real-life decision-

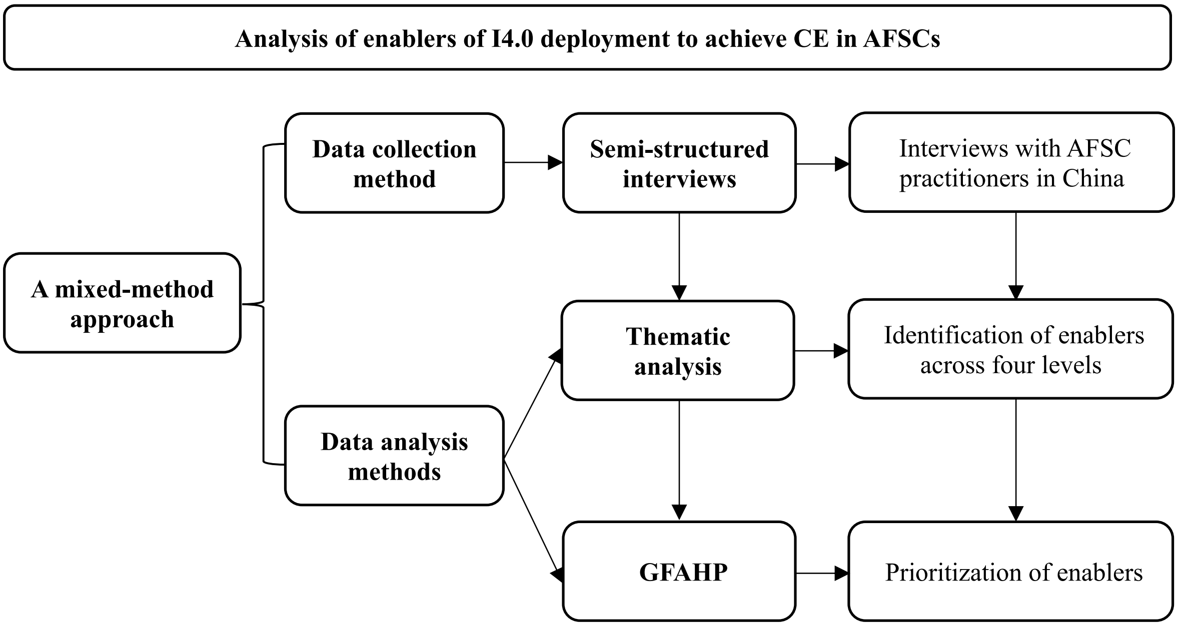

Fig. 2. Research methods adopted.

making problems is difficult when based on a single decision maker. Moreover, human decision-making and estimation processes are uncertain and vague (Che et al., 2020). GFAHP uses fuzzy set theory to prioritize enablers based on independent judgments by a group of experts, which has proved to be more realistic in real-life applications (Wang and Elhag, 2007). Second, other MCDM methods all have drawbacks. For example, AHP and FAHP can be used to determine the relative importance of variables, but their prioritization results are based on a single expert's judgements (Attajer et al., 2022). Interpretive structural modelling and total interpretive structural modelling can both be used to identify key variables by establishing interrelationships between them, but do not rank all the variables involved in a decision-making problem (Majumdar et al., 2021). The analytic network process is effective for identifying decision-making priorities with multi-attributes; however, its applicability is limited by its complex procedures and unwieldy model owing to the large number of variables involved. Graph theory and DEMATEL are effective for identifying relationships between variables, but not for prioritizing them. Finally, the interpretive ranking process can be used to rank a set of variables, but is difficult with more than 10 variables and the judgment process is highly subjective (Mangla et al., 2018). Thus, we selected a GFAHP to prioritize our enablers.

4. Empirical data collection

We collected our empirical data in China between December 2021 and February 2022. This three-month period provided us with sufficient opportunities to conduct face-to-face interviews with experienced AFSC practitioners. The specific period was selected for several reasons. First, in winter in northern China, the temperature drops rapidly and soil gradually freezes, making it difficult to cultivate outdoor plants for five to six months. Thus, intelligent greenhouses involving I4.0 technologies are widely deployed to tackle this issue. we were able to gain a deeper understanding and obtain valuable knowledge of how I4.0 technologies can be used to improve AFSCs because all our interviews were conducted following on-site visits. Second, winter was a valuable period in which to understand how to achieve CE relation to agri-chemical products, water resources, carbon dioxide, heat, and humidity. In particular, a deep understanding of intelligent greenhouse heating efficiency would not have been obtained in other seasons. Third, AFSCs in China are highly efficient during the winter months because off-season vegetables must still fully satisfy consumers' preferences. Thus, valuable knowledge on achieving CE in AFSCs could be obtained by interviewing AFSC stakeholders.

China's various climatic conditions are advantageous for different industries in different provinces. Therefore, we conducted our interviews in provinces that have widely applied facility agriculture. This involves using facilities such as monitoring and control systems, heat storage and release facilities, and lighting installations to support plant cultivation and production efficiently, effectively and economically (Li et al., 2011). We conducted interviews in Shandong province for several reasons. First, Shandong is one of the four main provinces (alongside Jangsu, Liaoning, Hebei) deploying facility agriculture in China. Approximately 60% of vegetables, 80% of aquatic products, and 86% of livestock products in Shandong are produced from facility agriculture (Dazhong Daily, 2023). Second, Shandong was the one of the first provinces to implement circular agriculture in China in 2002 (Chen et al., 2007). We believed that its long history of CE and facility agriculture would provide us with insights into our research topic. Third, we have wide connections with Shandong's agricultural research institutes, universities, enterprises, and agricultural governmental departments from our involvement in China-EU and China-UK collaboration projects. In particular, several Chinese professors with expertise in facility agriculture who had been collaborating with China's agri-food industry for more than 30 years were happy to introduce potential interviewees.

Based on our connections and partners' recommendations, we developed a preliminary list of 14 companies/institutions that might fulfil our criteria for empirical data collection. Regarding the sector criteria, first, the selected agri-food companies should be medium-sized or large companies that had applied I4.0 technologies. In Chinese agriculture, forestry, animal husbandry, and fisheries, companies with an annual operating income of five million yuan and above are classified as medium-sized enterprises (Ministry of Industry and Information Technology, 2018). Second, we aimed to understand enablers of I4.0 technology deployment to achieve CE of AFSCs. Thus, the selected agri-food companies should cover most roles of AFSCs (e.g., farmers, manufacturers, and regional agricultural governments) to ensure that our findings were not restricted to a particular I4.0 technology, waste management process, or sector and would be useful for general understanding of I4.0 technologies' role in facilitating CE (Eisenhardt and Graebner, 2007). Some companies did not meet the annual operating income requirements, did not apply I4.0 technologies, or only applied them in limited agricultural areas (e.g., irrigation). Thus, eight companies were ultimately selected, covering farming, manufacturing, agricultural technology, knowledge and research extension, and agricultural policy making.

We disseminated information on this project widely through WeChat groups, emails and phone calls to attract potential participants. As a result, 56 employees from chosen companies/institutions expressed interest in our study. However, we could not involve all of them in our study. At this stage, purposive sampling was used to recruit suitable interviewees, with specific criteria based on the research demands. First, participants had to be directly involved in I4.0 technology implementation to facilitate agricultural development. We insisted on this criterion because we believe that deep understanding of a phenomenon can only be obtained through close involvement, especially since I4.0 technologies have been applied in the agri-food industry for less than 15 years (Silveira et al., 2021). Second, potential interviewees must have been working in the agri-food industry or conducting relevant research for over ten years, to ensure that they had in-depth knowledge, experience, or skills relating to I4.0 technologies, CE, and AFSCs. Third, they must have middle- or senior-level management roles, or intermediate or senior professional titles to ensure that they could provide us with valuable information. Based on these criteria, we obtained a sample of 32 interviewees suitable for our study. We then contacted them by telephone and WeChat to check their availability for interview between December 2021 and February 2022.

We developed an interview guide through a round-table discussion with two professors in operations management. We then conducted pilot interviews with three Chinese AFSC practitioners to test the interview questions and gain more practical experience of interviewing. The pilot results suggested that we should ask more probing questions and assist respondents' understanding by providing more examples of I4.0 applications and explaining our theoretical framework. Thus, we modified the interview guide by adding some agriculture 4.0 examples and preparing more probing questions (see Appendix 1). We sent the interview guide to participants two days before their interviews to ensure that they had sufficient time to familiarize themselves with the research questions and prepare their answers. The interviews were recorded with interviewees' permission, and they were free to express their ideas relating to the questions being discussed. Many probing questions were asked to get participants to clarify their answers as necessary. Each interview lasted for 90 min on average, with some lasting more than 2 h. We followed Yin's (2009) 24-h rule in performing quick data analysis to identify the data saturation point. After interviewing all the participants, we conducted no further interviews because no new answers were emerging, resulting in a final sample size of 32 participants (see Table 2).

5. Data analysis and findings

We employed two data analysis methods in this study. We used

Table 2
Interviewee details.

Company/ Institution	Role and responsibility in AFSC	Interviewee's position	Relevant working experience (years)
A	**Farmer** responsible for vegetable production, focusing mainly on Chinese leaf	Production manager (A1)	15
		Quality assurance manager (A2)	12
		Marketing manager (A3)	16
		Technical director (A4)	13
B	**Farmer** responsible for vegetable production, focusing mainly on tomatoes, eggplants, and long beans	CEO (B1)	20
		Operations manager (B2)	10
		Production manager (B3)	14
		Human resource manager (B4)	15
C	**Farmer** responsible for vegetable production, focusing mainly on spring onions, cucumber, and celery	Technical director (C1)	10
		Stocking manager (C2)	10
		Planning manager (C3)	12
		Packaging manager (C4)	13
D	**Agricultural research institution** responsible for research and development for pest management, gene modification, agricultural information systems, and facility agriculture.	Professor of facility agriculture (D1)	20
		Professor of agricultural information systems (D2)	22
		Professor of food safety (D3)	24
		Professor of agricultural science and engineering (D4)	25
E	**Agricultural knowledge & technology extension** responsible for promoting new technologies and products, guiding farmers' production, increasing farmers' income, and revitalizing the rural economy.	Principle investigator of facility agriculture (E1)	28
		Principle investigator of circular agriculture (E2)	15
		Principle investigator of rural economy (E3)	20
		Principle investigator of agricultural environment protection (E4)	20
F	**Regional agricultural & rural government** responsible for promoting and reforming the city's agricultural science and technology system	Section chief of agriculture and information technology (F1)	20
		Section chief of agricultural education and technology (F2)	18
		Section chief of agricultural mechanization management (F3)	16
		Section chief of agricultural product quality and safety management (F4)	12
G	**Agricultural technology manufacturer** responsible for manufacturing water and fertilizer integration systems	Marketing manager (G1)	10
		Technical director (G2)	11
		CEO (G3)	18
		Regional manager (G4)	10
H	**Agricultural technology manufacturer** responsible for manufacturing intelligent greenhouses	Technical director (H1)	20
		Equipment director (H2)	15
		Engineering manager (H3)	25
		Import manager (H4)	16

thematic analysis to identify enablers, and utilized these as inputs into a GFAHP to prioritize them to gain an understanding of successful implementations of I4.0-enabled CE practices for AFSCs.

5.1. *Identification of enablers through thematic analysis*

We analyzed the qualitative data collected from semi-structured interviews using thematic analysis, which involved transcribing, editing, coding, categorizing, and reporting (see Fig. 3). We began by transcribing the interview audio files word-for-word to avoid missing any important elements. Each interview lasted between 45 and 75 min, resulting in three to five pages of transcript for each, totalling 128 pages. We then immersively read the transcripts several times to increase our familiarity with the data, and edited them to remove irrelevant data. During the coding process using NVivo 13, we paid particular attention to positive changes promised by I4.0 technologies for CE implementation, and environmental, supply chain, organizational, and individual factors facilitating this transition. Next, we linked codes with similar meanings and collapsed them into higher-order themes, drawing on established themes from relevant literature. In particular, we iteratively refined the codes and themes, moving back and forth between data and relevant literature. Finally, we used King and Horrocks' (2010) framework of first-order codes, second-order themes, and aggregate dimensions to present the results of our thematic analysis (see Table 3).

Our study provides deeper insights than others into achieving CE in AFSCs through I4.0 technology deployment. Our eight enablers of macro-level environments are connected with unique aspects of China. For example, its hierarchical cultural value orientation legitimizes unequal distributions of power, roles, and resources, thereby encouraging

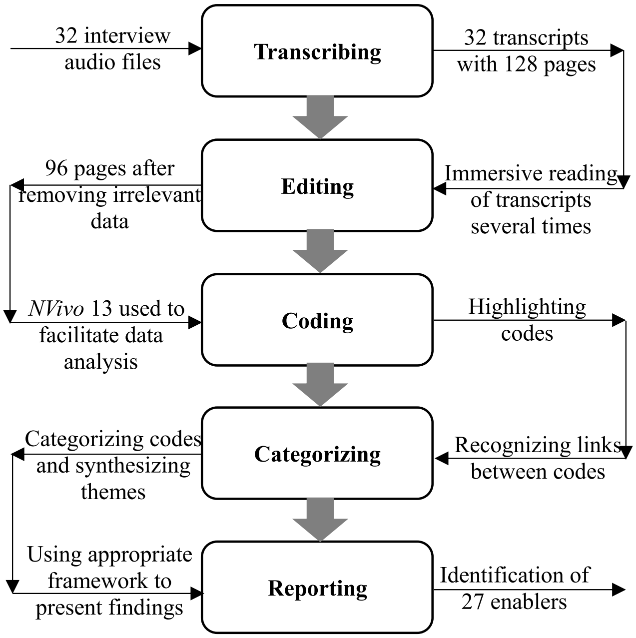

Fig. 3. Thematic analysis process.

Table 3
Empirical evidence of enablers of I4.0 technology deployment to achieve CE in AFSCs.

First-order codes	Second-order themes	Support from interviewees	Support from literature/ identification through interviews	Aggregate dimensions
"Many of China's policies have been deployed around digital China, rural revitalization, and digital rural."	Rural revitalization policy empowers agricultural digitalization (E1)	A1,A2,A3,A4,B1,B2,B3,B4,C1,C2, C3,C4,D1,D2,D,D4,E1,E2,E3,E4, F1,F2,F3,F4,G1,G2,G3,G4,H1, H2,H3,H4	Identification through our expert interviews	**Macro-level environments**
"China strengthens research and development of the agri-food industry."	Economic development to ensure continuous investment in agriculture 4.0 (E2)	A1,A2,A3,A4,B1,B2,B3,B4,C1,C2, C3,C4,D1,D2,D,D4,E1,E2,E3,E4, F1,F2,F3,F4,G1,G2,G3,G4,H1, H2,H3,H4	Identification through our expert interviews	
"Now, the agricultural department of the Chinese government is launching large-scale training for new farmers."	Large-scale training for new generation of farmers (E3)	A1,A2,A3,A4,B1,B2,B3,B4,C1,C2, C3,C4,D1,D2,D,D4,E1,E2,E3,E4, F1,F2,F3,F4,G1,G2,G3,G4,H1, H2,H3,H4	Identification through our expert interviews	
"In the past several years, most young people have gone out to work, leaving some people aged 50–60."	Aging rural and farming populations (E4)	A1,A2,A3,A4,B1,B2,B3,B4,C1,C2, C3,C4,D1,D2,D,D4,E1,E2,E3,E4, F1,F2,F3,F4,G1,G2,G3,G4,H1, H2,H3,H4	Identification through our expert interviews	
"There is no problem with the coverage of public networks of rural areas."	New infrastructure construction to enhance rural telecommunications infrastructure (E5)	A1,A2,A3,A4,B1,B2,B3,B4,C1,C2, C3,C4,D1,D2,D,D4,E1,E2,E3,E4, F1,F2,F3,F4,G1,G2,G3,G4,H1, H2,H3,H4	Luthra et al. (2020); Yadav et al. (2020); Zhao et al. (2024a)	
"The cultural environment of China facilitates policy implementation."	Hierarchical cultural value orientation supports agricultural policy implementation (E6)	A1,A2,A3,A4,B1,B2,B3,B4,C1,C2, C3,C4,D1,D2,D,D4,E1,E2,E3,E4, F1,F2,F3,F4,G1,G2,G3,G4,H1, H2,H3,H4	Identification through our expert interviews	
"Frequent extreme weather conditions such as floods, making us understand the necessity for reducing carbon emissions."	China's agriculture is highly dependent on the weather (E7)	A1,A2,A3,A4,B1,B2,B3,B4,C1,C2, C3,C4,D1,D2,D,D4,E1,E2,E3,E4, F1,F2,F3,F4,G1,G2,G3,G4,H1, H2,H3,H4	Identification through our expert interviews	
"During the 13th Five-Year Plan, the country proposed clearance work to reduce work intensity and manpower consumption."	Energy conservation and environmental protection (E8)	A1,A2,A3,A4,B1,B2,B3,B4,C1,C2, C3,C4,D1,D2,D,D4,E1,E2,E3,E4, F1,F2,F3,F4,G1,G2,G3,G4,H1, H2,H3,H4	Machado et al., 2021 (2021); Govindan (2023); Sindhwani et al. (2023); Zhang et al. (2023)	
"Governments build various traceability, information sharing, and production and sales information platforms to share information."	Deployment of various agricultural information systems to facilitate information sharing (S1)	A1,A2,A3,A4,B1,B2,B3,B4,C1,C2, C3,C4,D1,D2,D,D4,E1,E2,E3,E4, F1,F2,F3,F4,G1,G2,G3,G4,H1, H2,H3,H4	Identification through our expert interviews	**Meso-level supply chains**
"Autonomous driving is a relatively mature technology, and so is environmental detection."	High technology readiness for widely deployed I4.0 technologies (S2)	A1,A2,A4,B1,B2,B4,C1,C3,C4, D1,D2,D,D4,E2,E3,E4,F2,F3,F4, G1,G2,G4,H1,H2,H3	Sharma et al. (2021); Govindan (2023)	
"China has food security issues because agriculture depends highly on the weather."	Food security issues accelerate applications of I4.0 technologies (S3)	A1,A2,A3,A4,B1,B2,B3,B4,C1,C2, C3,C4,D1,D2,D,D4,E1,E2,E3,E4, F1,F2,F3,F4,G1,G2,G3,G4,H1, H2,H3,H4	Identification through our expert interviews	
"We develop I4.0 and CE because of our competitors."	Pressure from competitors (S4)	A1,A2,A3,A4,B1,B2,B3,B4,C1,C2, C3,D2,D1,F3,F4,G1,G2,G3,G4, H1,H2,H3,H4	Cater et al. (2021); Sharma et al. (2021); Vimal et al. (2022); Govindan (2023)	
"Trust is an important factor, especially when we are at the initial stage of applying relevant information technologies in agriculture."	Trust between service/equipment providers and farmers (S5)	A1,A2,A3,A4,B1,B2,B3,B4,C1,C2, C3,C4,D1,D2,D,D4,E1,E2,E3,E4, F1,F2,F3,F4,G1,G2,G3,G4,H1, H2,H3,H4	Govindan (2023)	
"When a certain technology is at its best, invite similar people to watch or observe it."	On-site observation and practical training to facilitate KMob across AFSCs (S6)	A1,A2,A3,A4,B1,B2,B3,B4,C1,C2, C3,C4,D1,D2,D,D4,E1,E2,E3,E4, F1,F2,F3,F4,G1,G2,G3,G4,H1, H2,H3,H4	Identification through our expert interviews	
"China's large-scale agriculture is now gradually accelerating."	Accelerating deployment of large-scale agriculture (S7)	A1,A2,A3,A4,B1,B2,B3,B4,C1,C2, C3,C4,D1,D2,D,D4,E1,E2,E3,E4, F1,F2,F3,F4,G1,G2,G3,G4,H1, H2,H3,H4	Identification through our expert interviews	
"I4.0 technologies facilitate precise application of pesticides, and thereby reduce fertilizer."	Reducing chemical fertilizer and water resource usage (O1)	A1,A2,A3,A4,B1,B2,B3,B4,C1,C2, C3,C4,D1,D2,D,D4,E1,E2,E3,E4, F1,F2,F3,F4,G1,G2,G3,G4,H1, H2,H3,H4	Identification through our expert interviews	**Meso-level organizations**
"Fertilizers can cause harm to the environment through penetration or volatilization."	Reducing opportunities to contaminate groundwater (O2)	A1,A2,A3,A4,B1,B2,B3,B4,C1,C2, C3,C4,D1,D2,D,D4,E1,E2,E3,E4, F1,F2,F3,F4,G1,G2,G3,G4,H1, H2,H3,H4	Identification through our expert interviews	
"Applying digital technologies can help to reduce carbon emissions."	Reducing carbon emissions (O3)	A1,A2,A3,A4,B1,B2,B3,B4,C1,C2, C3,C4,D1,D2,D,D4,E1,E2,E3,E4, F1,F2,F3,F4,G1,G2,G3,G4,H1, H2,H3,H4	Gebhardt et al. (2022); Zhang et al. (2023); Piepoli et al. (2024); Zhao et al. (2024a)	

(*continued on next page*)

Table 3 (*continued*)

First-order codes	Second-order themes	Support from interviewees	Support from literature/ identification through interviews	Aggregate dimensions
"Government provides subsidies for leading enterprises and industrial parks."	Government subsidies for enterprises to deploy I4.0 technologies (O4)	A1,A2,A3,A4,B1,B2,B3,B4,C1,C2, C3,C4,D1,D2,D,D4,E1,E2,E3,E4, F1,F2,F3,F4,G1,G2,G3,G4,H1, H2,H3,H4	Jain and Ajmera (2021); Zhao et al. (2024a); Pandey et al. (2024)	
"One of the key advantages of applying I4.0 technologies is to reduce the cost of human resources."	Reducing human resource inputs (O5)	A1,A2,A3,A4,B1,B2,B3,B4,C1,C2, C3,C4,D1,D2,D,D4,E1,E2,E3,E4, F1,F2,F3,F4,G1,G2,G3,G4,H1, H2,H3,H4	Luthra et al. (2020); Zhang et al. (2023); Zhao et al. (2024a)	
"Large equipment has relatively high maintenance costs. Others are just an anti-aging process."	Low maintenance costs of digital agricultural equipment (O6)	A1,A4,B4,C1,C2,C3,C4,D1,D2,D, D4,E1,E2,E3,E4,F1,F2,F3,G4,H1, H2	Jamwal et al. (2021); Govindan (2023)	
"Farmers with more than 200 acres of land appreciated the technology because their profits increased."	Productivity improvement and profit increases (O7)	A1,A2,A3,A4,B1,B2,B3,B4,C1,C2, C3,C4,D1,D2,D,D4,E1,E2,E3,E4, F1,F2,F3,F4,G1,G2,G3,G4,H1, H2,H3,H4	Sharma et al. (2021); Govindan (2023); Zhang et al. (2023)	
"Our management team are open to new technology that can make positive changes to our organization."	Top management team's support (O8)	A1,A2,A3,A4,B1,B2,B3,B4,C1,C2, C3,C4,D1,D2,D,D4,E1,E2,E3,E4, F1,F2,F3,F4,G1,G2	Govindan (2023); Zhang et al. (2023); Zhao et al. (2024a); Pandey et al. (2024)	
"Some farmers are happy to communicate with others, especially sharing information with research institutes."	Willingness to learn new knowledge or deploy I4.0 technologies (P1)	A1,A2,A3,A4,B1,B2,B3,B4,C1,C2, C3,C4,D1,D2,D,D4,E1,E2,E3,E4, F1,F2,F3,F4,G1,G2,G3,G4,H1, H2,H3,H4	Cater et al. (2021); Jain and Ajmera (2021)	**Micro-level practitioners**
"Farmers recognize the importance of I4.0 and CE."	Knowledge of I4.0 and CE (P2)	A1,A2,A3,A4,B1,B2,B3,B4,C1,C2, C3,C4,D1,D2,D3,E3,E4,F1,F2,F3, F4,G1,G4,H1,H2,H3,H4	Luthra et al. (2020); Cater et al. (2021); Govindan (2023)	
"Agricultural technicians are usually graduates from agricultural colleges. Therefore, they have some digital skills."	Enhanced digital skills (P3)	A1,A2,A3,B2,B3,B4,C1,C2,C3,C4, D1,D2,D,D4,E1,E2,E3,E4,F1,F4, G1,G2,G3,G4,H3,H4	Identification through our expert interviews	
"Most farmers are developing circular agriculture based on the government's guidance."	Obeying expectations of authorities (P4)	A1,A2,A3,A4,B1,B2,B3,F4,G1, G2,G3,G4,H1,H2,H3,H4	Identification through our expert interviews	

tolerance of and obedience to the expectations of those in roles of greater status or authority (Schwartz, 2006). This cultural environment supports agricultural policy implementation, especially of policies made by China's State Council, such as those in the 2023 No. 1 Central Document on strengthening agricultural infrastructure construction and agricultural technology and equipment development (National Food and Strategic Reserves Administration, 2023). Moreover, as one interviewee commented, the Chinese government has launched large-scale, multi-form vocational skills training for the new generation of farmers: *"The training is to improve the quality of farmers. It is crucial for farmers to have food safety awareness by understanding agricultural inputs and plant growth process."* Another interviewee stated: *"In the past few years, most young people have gone elsewhere to work, leaving some people aged 50 – 60 or even 70 years old who are still farming. It is difficult for those people to accept new knowledge."*

In the category of meso-level supply chains, we identify seven enablers that may contribute to the deployment of I4.0 technologies to achieve CE in AFSCs. For example, China has deployed agricultural information platforms to facilitate information sharing: *"Various traceability, information interconnection, agricultural machinery monitoring, agricultural information acquisition, and production and sales docking platforms were built to ensure that AFSC practitioners can receive relevant information as quickly as possible."* For some I4.0 technologies, such as IoT to monitor environments, water, and fertilizer integration systems, and intelligent greenhouses, the readiness level is high because these technologies are widely deployed across AFSCs. Successful deployment of these cutting-edge technologies is determined by two interrelated factors: technological readiness and relevant applications. One interviewee stated: *"Some technologies are advanced technologies, and if the implemented path cannot match these technologies, it would be not worth using them."*

In the category of meso-level organizations, we identify eight enablers closely linked with benefits and measures adopted to apply I4.0 technologies to achieve CE. The benefits include reducing use of chemical fertilizers and water resources (O1), reducing contamination of underground water (O2), reducing carbon emissions (O3), and reducing human resource inputs (O5). One interviewee reinforced: *"In terms of application of water and fertilizer integration systems in northern China, agricultural water savings of more than 70% can be achieved and agricultural sustainability can be improved. Moreover, agrichemical leakage pollution can also be minimized."* Among the measures adopted, several interviewees noted on-site observations and practical training to facilitate KMob across AFSCs (O7), because the Chinese believe that *"seeing is believing"*. One interviewee said: *"The most feasible way to facilitate KMob is on-site observation. For example, invite other AFSC practitioners to watch or observe how I4.0 technology works and what achievements can be made by these technologies. Farmers do not like listening to lecturers."*

Finally, we identify four enablers of micro-level practitioners: willingness to learn new knowledge or deploy I4.0 technologies (P1), knowledge of I4.0 and CE (P2), enhanced digital skills (P3), and obeying expectations of authorities (P4). We took Chinese people's characteristics into particular consideration because they are deeply affected by the country's hierarchical cultural value orientation.

Unlike similar studies (e.g., Yadav et al., 2020; Behl et al., 2023; Govindan, 2023; Kumar et al., 2023) that have focused on analyzing enablers of I4.0 technology deployment to achieve CE in supply chains, we believe that successful deployment of I4.0 technologies is determined by a combination of enablers arising from macro-level environments, meso-level supply chains, meso-level organizations, and micro-level practitioners. Analyzing enablers from fewer levels would be inadequate to address this research context.

5.2. Prioritization of enablers using GFAHP

We implemented a six-step GFAHP to prioritize the 27 identified enablers. Fig. 4 illustrates this process.

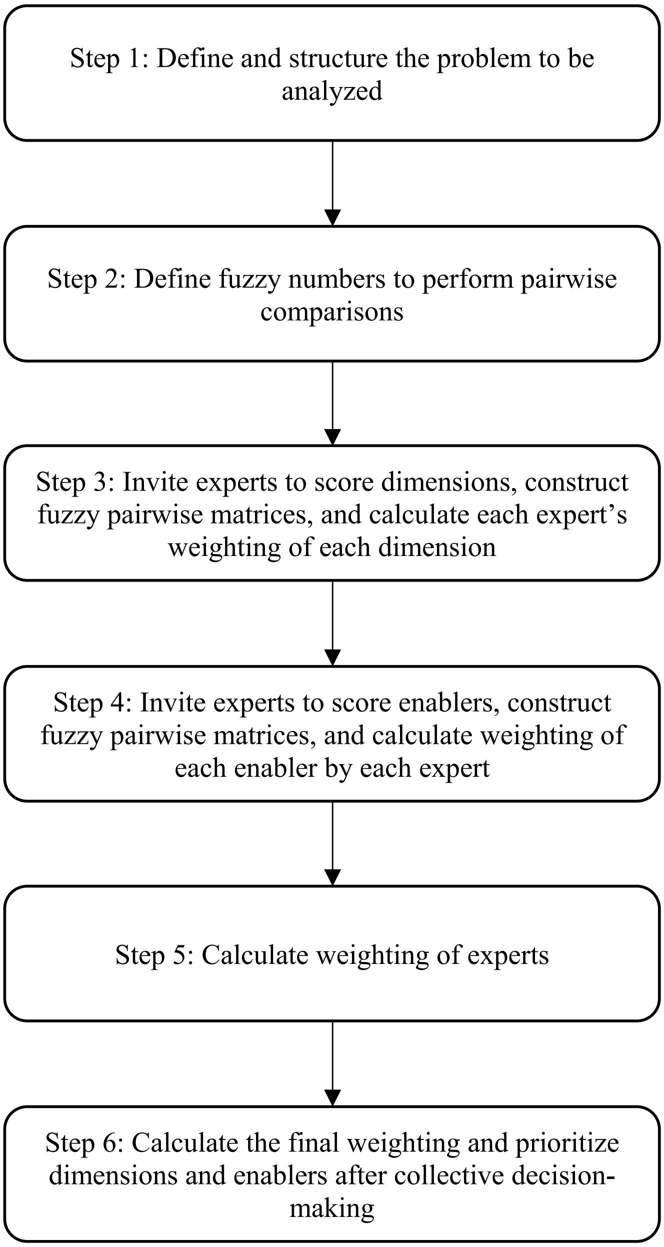

Fig. 4. A six-step GFAHP.

Step 1 **Define and structure the problem to be analyzed.** In this step, we categorized the 27 identified enablers into four dimensions: environments, supply chains, organizations, and practitioners (see Table 2). We used these as inputs for further analysis.

Step 2 **Define fuzzy numbers to perform pairwise comparisons.** We integrated fuzzy set theory into this study to improve the traditional AHP algorithm and enhance the decision makers' inputs and precision. In traditional AHP, we initially used a nine-level relative importance scale to rate relationships between two alternatives, with 1, 3, 5, 7, and 9 representing equal, moderate, strong, very strong, and extremely strong importance respectively. However, this process may be imprecise because it requires expert judgements, and experts may be unable to assign exact numerical values to their preferences owing to limited information or capability (Liu et al., 2020). To alleviate this, we used a fuzzification process to convert crisp values into fuzzy values to regulate the degree of membership. Thus, we describe the relationship between two alternatives with a fuzzy range rather than a definite value. For example, we use (3,4,5) to represent that the importance between two alternatives is between moderate and strong importance. Appendix 2 shows the fuzzy scale of relative importance.

Step 3 – Invite experts to score dimensions, construct fuzzy pairwise matrices, and calculate each expert's weighting of each dimension. There is no scholarly consensus on how many experts should be invited to participate in a group decision-making problem. However, Xu et al. (2015) suggest a minimum of 11 for large group decision making. In this study, we used a medium-sized rather than large decision-making group because many challenges arise with increased group size, such as complexity and cost (Tang and Liao, 2021). We invited ten experts involved in the empirical data collection who had expertise in I4.0 and CE and decision-making experience to rate relationships between pairs of enablers. Their scores were then plugged into pairwise matrices. For example, M^n represents the pairwise matrix after scoring by expert n. For the element m_{ij}^n in matrix M^n, if $i = j$, then $m_{ij}^n = (1,1,1)$.

$$M^n = \left\{m_{ij}^n\right\}, i = 1,2,3\cdots10, j = 1,2,3\cdots10$$

where $m_{ij}^n = (a^1, a^2, a^{13}), m_{ij}^n = \left\{m_{ij}^n\right\}^{-1}$

Next, we calculated the weighting of each dimension based on the expert's matrix. To achieve this, we first obtained the fuzzy geometric mean value S_i for each expert involved in the decision-making process based on the following equation:

$$S_i^n = \sum_{j=1}^{n} m_{ij}^n \left[\sum_{i=1}^{n}\sum_{j=1}^{n} m_{ij}^n\right]^{-1}, \text{where } S_i^n = \{s_i\}, s_i = (s_1, s_2, s_3)$$

We then performed a de-fuzzification process on S_i to convert it into a one-dimensional vector $\overline{S_i^n}$:

where $\overline{s_i} = \dfrac{s_1 + 2^* s_2 + s_3}{4}$

We normalized S_i to obtain the weighting of each dimension for each expert based on the following equation:

$$W^n = \frac{\overline{S_i}}{\sum_{i=1}^{n} \overline{S_i}}$$

We calculated the largest eigenvalue of matrix $\lambda_{max} = \frac{\sum (AW)_i}{NW_i}$. Similarly, we initially de-fuzzified the expert's fuzzy pairwise matrix, using the same process as for the defuzzification calculation method for vector $\overline{S_i^n}$. We then labelled matrix M^n, where n represents the number of dimensions ($n = 4$).

Finally, we checked the consistency of the experts' opinions. The consistency ratio (CR) is used to verify whether the results of comparisons are acceptable. A CR of less than or equal to 0.10, indicates uniformity in the experts' judgments (Saaty, 1996). The CR is obtained using the following formula, where RI represents the average random consistency index, which relates only to the order n of the matrix. In this case, the RI is 0.9 because we have four dimensions.

$$CR = \frac{CI}{RI}, CI = \frac{(\lambda_{max} - n)}{(n - 1)}$$

We obtained the weighting of dimension WD_i^n for each expert and the CR for dimension calculation C_D^n after each expert's decision, where i represents the four dimensions from 1 to 4, and n represents each expert's code. Our consistency tests produced a value of CR less than or equal to 0.10, indicating consistency between the ten experts.

Step 4 – Invite experts to score enablers, construct fuzzy pairwise matrices, and calculate the weighting of each enabler by

each expert. The ten experts involved in *Step 3* were asked to conduct pairwise comparisons of the enablers within each dimension to produce fuzzy pairwise matrices. We then repeated the same calculation process as in *Step 3* to obtain the weighting of each enabler by each expert, and conducted consistency checking. The results indicated consistency between the ten experts has been reached. Finally, we uniformly marked the enablers' weightings as WB_i^n, where i represents the enabler and n represents the experts' coding.

Step 5 – Calculate the weighting of experts. The ten experts were given decision weightings to assess their logic. The weight of each decision maker is shown in Appendix 3. To achieve this, we calculated the average CR of each expert as a basis for measuring the logic:

$$C_R^n = \frac{C_E^n + C_O^n + C_p^n + C_S^n}{4}$$

To assess the logic, we introduced variable P^n to calculate the weighting of the expert, calculated as follows:

$$P_n = \frac{1}{1 + aC_R^n}, a > 0, n = 1, 2......m$$

In this formula, constant a has a value of 10, and n represents the code given by the expert. P_n^* denotes the weighting by the decision maker, calculated as follows:

$$P_n^* = \frac{P_n}{\sum_{n=1}^{m} P_n}$$

Step 6 – Calculate the final weighting and prioritize dimensions and enablers after collective decision making. In *Steps 3* and *4*, we calculated the weighting of each dimension and each enabler by each expert. In *Step 6*, we used these results as inputs to obtain the final weightings of dimensions and enablers following the ten experts' collective decision making. The formulae used to calculate these final weightings are as follows.

$$WD_i^{Group} = \sum_{n=1}^{10} P_n^* * WD_i^n$$

$$WB_i^{Group} = \sum_{n=1}^{10} P_n^* * WD_i^n * WB_i^n$$

Table 4 shows the final ranking of categories and enablers after collective decision-making.

We first present the results of the category rankings, and then discuss the enablers in each category. In our results for category ranking, macro-level environments are ranked first, followed by meso-level organizations, meso-level supply chains, and micro-level practitioners. China's cultural value orientation is particularly hierarchical, emphasizing adherence to and preservation of traditional and externally imposed ideas and preferences (Schwartz, 2006). As long as the central government specifies future directions such as the rural revitalization policy and new infrastructure construction, resources will be used to support these developments. Resources are normally prioritized for leading enterprises that have wide connections with farmers and some foundation to develop cutting-edge technologies. One interviewee stated: *"Leading enterprises at a certain level, such as municipal, provincial, and national levels – based on their capability to drive the whole industry, government would provide subsidies to* support *their development."* These leading enterprises are normally focal companies of AFSCs. The financial resources acquired can also be used to train employees.

In the category of macro-level environments, rural revitalization policies empowering agricultural digitalization (E1) are ranked first, followed by new infrastructure construction to enhance rural telecommunications infrastructure (E5), a hierarchical cultural value orientation supporting agricultural policy implementation (E6), and large-scale training for the new generation of farmers (E3). Note that the government allocates financial resources specifically to support professional training. One interviewee stated: *"The local government spent about five to six million per year to* support *professional, agricultural technology, and testing training. Experts are invited to give lectures to farmers every year, and training is provided across different regions."* Zhao et al. (2024a) highlight that I4.0 technologies can help to achieve various economic,

Table 4
Final ranking of categories and enablers.

Category of enablers	Relative weighting	Relative rank	Specific enabler	Relative weighting	Relative rank	Global weighting	Global rank
Macro-level environments	0.505568	1	E1	0.243007	1	0.076673	3
			E2	0.085516	5	0.026982	9
			E3	0.120091	4	0.037891	7
			E4	0.051203	7	0.016156	14
			E5	0.241426	2	0.076174	4
			E6	0.136990	3	0.043223	6
			E7	0.037172	8	0.011728	16
			E8	0.084594	6	0.026691	10
Meso-level supply chains	0.064766	3	S1	0.324526	1	0.020046	13
			S2	0.116383	4	0.007189	22
			S3	0.109265	5	0.006749	23
			S4	0.051884	7	0.003205	26
			S5	0.201780	2	0.012464	15
			S6	0.129793	3	0.008017	19
			S7	0.066369	6	0.004100	25
Meso-level organizations	0.331286	2	O1	0.113863	4	0.010087	18
			O2	0.087324	5	0.007736	20
			O3	0.130586	3	0.011569	17
			O4	0.085233	6	0.007551	21
			O5	0.049026	7	0.004343	24
			O6	0.034674	8	0.003027	27
			O7	0.255967	1	0.022677	11
			O8	0.243327	2	0.021557	12
Micro-level practitioners	0.09838	4	P1	0.506966	1	0.270781	1
			P2	0.330056	2	0.176289	2
			P3	0.098257	3	0.052481	5
			P4	0.064721	4	0.034569	8

environmental, and social benefits, but the adoption process in supply chains will involve with social, economic, and environmental forces. Similarly, Sindhwani et al. (2023) propose that without the support of external environments (e.g., economic and policy), successful adoption of I4.0 technologies towards decarbonization cannot be achieved. Both their study and with Pandey et al. (2024) indicate the importance of supportive government policies for adopting I4.0 to achieve sustainable supply chains.

The category of meso-level organizations is prioritized second, because organizations are the main adopters of I4.0 technologies. The results suggest that organizations adopt I4.0 technologies for various reasons, with productivity improvement and profit increases (O7) ranked highest, followed by top management team's support (O8), reducing carbon emissions (O3), reduced use of chemical fertilizer and water resources (O1), reducing opportunities to contaminate water (O2), government subsidies for enterprises to deploy I4.0 technologies (O4), reducing human resource inputs (O5), and low maintenance costs of digital agricultural equipment (O6). Our results indicate that highly ranked enablers are all relevant to cost reduction, profit increases, and environmental protection. This is consistent with most existing studies. For example, Machado et al., 2021 (2021) state that top management commitment is the main influence on integration of I4.0 and supply chain sustainability, which in turn activates internal innovation processes, knowledge sharing and communication, and employees' empowerment. Faisal (2023) reveals that successful application of I4.0 technologies in supply chains facilitates cooperation and knowledge sharing between supply chain partners, and therefore enhances the supply chain's circular performance. Moreover, organizational-level enablers are closely connected with China's PESTEL environments. For example, China has declared its intention to reach peak carbon emissions by 2030 and achieve carbon neutrality by 2060. This means that it needs to adopt various measures to reduce carbon emissions, particularly in the agricultural sector, because half of greenhouse gas emissions are from China's agricultural production (Liu et al., 2023). Interestingly, low maintenance costs of digital agricultural equipment (O6) is ranked last in this category. Our interviewees highlighted two reasons: (1) existing Chinese farmers are relatively old and have relatively little knowledge, so they are not good at maintaining equipment; and (2) I4.0 integrated agricultural technologies are new, so farmers do not have extensive management experience of maintaining and using the equipment.

The meso-level supply chain category of enablers is ranked third. In China's PESTEL environments, leading enterprises are prioritized to receive resources to facilitate their development. Acting as focal companies, these enterprises have power to govern supply chains. In this category, the first three enablers are deployment of various agricultural information systems to facilitate information sharing (S1), trust between service/equipment providers and farmers (S5), and on-site observations and practical training to facilitate KMob across AFSCs (S6). Eslami et al. (2023) demonstrate that adopting I4.0 technologies facilitates knowledge sharing across supply chains, but they provide limited evidence of channels or approaches that might be used. Our findings reveal that focal companies disseminate knowledge across whole supply chains by deploying agricultural information systems. From our narrative analysis, we conclude that the key factors enabling other AFSC stakeholders to adopt I4.0 technologies are wide dissemination of information on I4.0 technologies combined with practical training sessions.

Finally, the micro-level practitioner category of enablers is ranked last in the priority list. In this category, willingness to learn new knowledge or deploy I4.0 technologies (P1) is ranked highest, followed by knowledge of I4.0 and CE (P2), enhanced digital skills (P3), and obeying expectations of authorities (P4). We assume that willingness to learn new knowledge is prioritized because I4.0 integrated agricultural technologies are a fast-changing area and AFSC practitioners must be keen to learn new knowledge. One interviewee stated: *"We want to share knowledge with farmers, but they are limited by their limited knowledge, age and stubborn ideas."* Previous studies have explored enablers of I4.0 deployment to achieve CE mainly from the environment, supply chain, and organizational perspectives, whereas very few have taken individual-level enablers into consideration. For example, Jain and Ajmera (2021) identify enablers from technological, environmental, and organizational perspectives and Zhao et al. (2024a) illustrate enablers from the organizational and environmental perspectives. Our study differs from existing studies by considering individuals knowledge, skills, and willingness.

6. Discussion

In this section, we discuss our findings in relation to previous literature, and thereby identify several unique contributions to existing knowledge while answering our two research questions. First, the majority of our 27 identified enablers are new to the domain of deploying I4.0 for CE success. Second, to our knowledge, this is the first study to use a GFAHP to prioritize enablers of I4.0 technology deployment to achieve CE, therefore, yielding rich insights into rankings of enablers, dimensions of enablers, and enablers within each dimension. Third, our study extends the applicability of GT to the I4.0 and CE domains. Finally, we make practical suggestions for facilitating I4.0 technology adoption to achieve CE.

6.1. Contributions to knowledge

Comparison of the enablers identified in this study with those in the literature reveals that most are new to deploying I4.0 technologies to achieve CE in AFSCs. For example, we identify 14 enablers mentioned by few previous scholars (see Table 3), including deployment of various agricultural information systems to facilitate information sharing and a hierarchical cultural value orientation supporting agricultural policy implementation and accelerating deployment of large-scale agriculture. This may be for two reasons. First, we conducted a more comprehensive investigation by using GT to identify enablers at four different levels, an approach rarely adopted to explore similar issues. Previous studies have identified I4.0 implementation enablers mainly from technological, organizational, and individual perspectives (Devi et al., 2021; Subramanian et al., 2021; Kee et al., 2023), neglecting the environmental and individual perspectives. Second, we gained deep insights into the phenomenon by considering China's unique PESTEL contexts. However, several of our enablers support those in the literature. For example, Rajput and Singh (2019) highlight 26 enablers, including big data, cloud manufacturing, and collaborative robotics between I4.0 and supply chain CE. De Mattos Nascimento et al. (2024) reinforce that additive manufacturing (AM), AR/VR, cloud computing, advanced robotics, and cyber-physical systems can be used to improve CE in supply chains. Gebhardt et al.'s (2022) study illustrates that IoT, blockchain, AM, BDA, cyber-physical systems and cloud computing are the main enabling I4.0 technologies for building a digital circular supply chains, and in turn circular networks, supporting cooperative recycling and streamlining of waste. Bai et al. (2020) assess the sustainability impacts of I4.0 technologies and conclude that nanotechnology, mobile technology, simulation, and drones have the highest impacts on food and beverage industries. Our study differs from most existing studies in showing that I4.0 technologies such as blockchain, AR/VR, and robotics are not widely deployed in China's agri-food industry, owing to high deployment costs and increased terminal logistics. Chinese AFSC practitioners rely on advanced sensor-enabled water-and-fertilizer integration systems, IoT-enabled environmental monitoring systems, drones, automated irrigation systems, and advanced sensors (e.g., temperature, light, humidity, and carbon dioxide concentration) to reduce chemical fertilizer and water resource usage, human resource inputs, and carbon emissions. Most studies adopt technological, social, and economic perspectives to identify enablers, neglecting the organizational and practitioner dimensions. For example, Piepoli et al. (2024) find various motivations for companies' deployment of I4.0 technologies, such as achieving energy and logistics efficiency, tracking recyclable components, eliminating non-value-added tasks, and reducing production costs. Spaltini et al. (2021) identify 16 enablers of I4.0 technology to achieve CE, such as reducing environmental emissions and waste, using resources more efficiently, and optimizing energy consumption. Our results support their findings, but differ in identifying context-specific enablers deeply connected with China's AFSCs, such as reducing chemical fertilizer and water resource usage, reducing the chances of contaminating groundwater, meeting the expectations of authorities, and constructing new infrastructure to enhance rural telecommunications. Hussain and Malik (2020) indicate 13 organizational enablers that may facilitate the transition toward CE. Similar enablers noted in our study include understanding of CE insights, reduced use of hazardous materials, and sustainability awareness. Bag et al. (2021) determine key resources that can be used to leverage I4.0-enabled CE, including production systems, human resources, project management, management leadership, green logistics, green design, information technology, BDA, and collaborative relationships. We obtain similar results, but include more perspectives in our analysis, such as the country's cultural value orientation, personal characteristics, and policy frameworks. Zhang et al. (2023), Kumar et al. (2023), and Khanzode et al. (2023) all present similar frameworks of enablers, drivers, and critical success factors relevant to I4.0 adoption to facilitate supply chains' CE transition. Enablers frequently mentioned in these studies include cost savings and profit maximization, regulatory pressures, knowledge of CE and I4.0, and management leadership. Our study partially supports their findings.

Our prioritization results also differ from those in the literature. For example, Khan et al.'s (2024) study of enablers of CE implementation in supply chains shows that consumer attitudes, top management commitment, economic incentives, and policies and legal frameworks are critical to implementing CE. Sharma et al.'s (2021) ranking of drivers of I4.0 adoption to achieve supply chain sustainability shows that supply chain practitioners deploy I4.0 technologies to enhance productivity, reduce emissions, and engage in non-invasive interactions. Jamwal et al. (2021) reveal 25 enablers of I4.0 deployment to develop sustainable frameworks. The most important of these include real-time tracking, KM promotion in supply chains, and educating society for sustainability. Our findings differ in identifying willingness to learn new knowledge or deploy I4.0 technologies, knowledge of I4.0 and CE, rural revitalization policy, and new infrastructure construction as key enablers. Behl et al.'s (2023) analysis of I4.0 and CE enablers shows that the policy framework is the most critical enabler. We confirm that various policies, such as on rural revitalization and new infrastructure construction, play important roles in facilitating AFSC practitioners' adoption of I4.0 technologies. We extend Behl et al.'s (2023) work by proposing that individuals' willingness to adopt I4.0 technologies and their knowledge of I4.0 and CE are also critical, and that their willingness is deeply affected by external PESTEL environments. Hussain and Malik (2020) consider a favourable organizational culture to be a prerequisite for activating I4.0-enabled CE. This is unsupported by our findings. Rather, we propose that organizations adopt I4.0 technologies to achieve CE for various economic and environmental benefits. Our results indicate that China's hierarchical cultural value orientation is a prerequisite for activating I4.0-enabled CE. Thus, our results, like those of Ghoreishi and Happonen (2020), indicate that policy frameworks, enhanced digital skills, and knowledge of I4.0 and CE are key enablers of CE.

6.2. Theoretical contributions

Ours appears to be the first study grounded in GT to explore enablers of I4.0 technology deployment to achieve CE in AFSCs, thereby extending GT's applicability. GT aims to provide a general framework to understand a social reality that may hold true for different social cultural contexts, and indeed over different periods of time (Mills, 1959). Previous studies have integrated various theories to investigate I4.0-enabled CE for supply chains, including the dynamic capability view, middle-range theory, RBV, CSF, and TOE (De Sousa Jabbour et al., 2022; Govindan, 2023; Lu et al., 2024; Zhao et al., 2024a), but few studies have used GT to explore the issue. Spina et al. (2016) develop a GT for purchasing and supply management research, Treiblmaier (2018) utilizes GT to investigate the impact of blockchain on supply chains, and Zhao et al. (2024d) employ GT to build a multi-level supply chain resilience framework. In our study, we take an initial step in investigating potential facilitators of CE in AFSCs in an I4.0 context. Our results indicate that I4.0-enabled CE in AFSCs depends on the collective efforts of individuals, organizations, supply chains, and external PESTEL environments (see Fig. 5). We also shed light on the effective role of a country's cultural value orientation in facilitating organizations' adoption of I4.0 to achieve CE, a factor seldom mentioned in previous research. Previous studies have considered organizational culture only as an enabler of I4.0 technology adoption. Our study reveals that in China's hierarchical cultural environment, synergies can be achieved across individuals, organizations, and AFSCs. Unlike most existing studies in this area, we also take individual characteristics into consideration.

6.3. Managerial and practical implications

This study also has managerial and practical implications for policymakers, AFSC managers, and directors of manufacturing companies producing I4.0 technologies.

With regard to the implications for policymakers, we suggest that they should foster appropriate environments to facilitate I4.0 technology deployment to achieve CE in AFSCs. This is supported by our finding that macro-level environments are ranked first among the four categories of enablers. We make several practical suggestions for policymakers. First, continuous investment is needed in development and deployment of digital infrastructure, especially in rural areas with many agri-food enterprises. This includes investing in network infrastructures (e.g., 5G) and providing subsidies or incentives for agri-food companies to adopt digital technologies. Second, public awareness and engagement must be enhanced by building various platforms for traceability, information sharing, and production and sales to enable AFSC practitioners share their experiences relating to I4.0-enabled CE. Third, technological innovation must be supported by providing funding for R&D initiatives in I4.0 technologies and pilot programmes for testing I4.0-enabled CE. Finally, policymakers should monitor and evaluate I4.0 technology deployment processes to maintain relevant strategies.

Regarding the implications for AFSC managers, our suggestions focus on AFSCs' focal companies, because they have the power to manage,

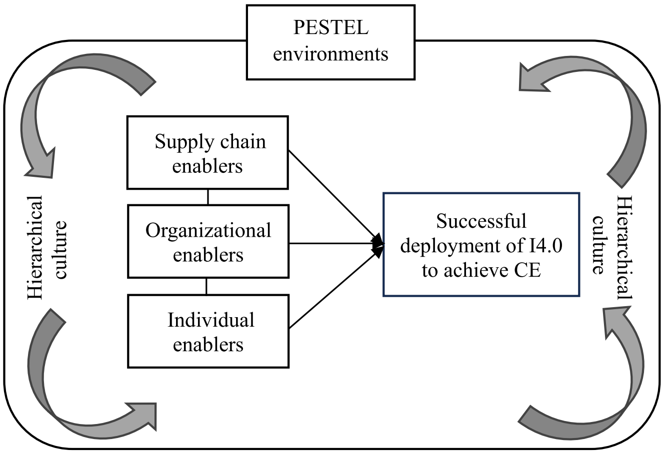

Fig. 5. An evaluated grand framework for I4.0-enabled CE.

coordinate, and oversee entire supply chain networks. First, AFSC managers of focal companies should deploy chain-wide KMob activities. This could be achieved by organizing practical rather than theory-based training sessions to disseminate knowledge relevant to I4.0 and CE. Our findings indicate that willingness to learn new knowledge and knowledge of I4.0 and CE are ranked first and second in the priority list. However, our interviewees criticized AFSCs' KMob processes for being theoretical and lecture-based, deterring farmers from learning new knowledge. Second, focal companies in AFSCs tend to have sufficient financial resources for this purpose. Thus, we suggest that they should collaborate with farmers or farmers' cooperatives to pilot projects relevant to I4.0-enabled CE and disseminate successful experiences to the whole AFSCs. Finally, focal companies should develop industry standards, such as certification programmes to promote efficient water and agrichemical use. This will encourage other AFSC stakeholders to use I4.0 technologies.

Regarding the implications for manufacturing directors, our findings suggest that skills gaps still impede AFSC practitioners from adopting I4.0 technologies. Thus, we suggest that manufacturing directors should actively collect consumer feedback relating to I4.0 technology users' experiences and make relevant changes. For example, the control interfaces of I4.0-enabled agricultural technologies should be simplified into no more than three levels, and voice-controlled interfaces should be developed to encourage their dissemination.

7. Conclusions

This study was triggered by an exponential rise in interest in I4.0-enabled CE in supply chains. Despite increased practitioner and academic interest, theory-based research is lacking on enablers of I4.0 technology deployment to achieve CE in AFSCs. Following Rosa et al.'s (2020) call, we propose a theoretical framework grounded in GT to address existing research gaps and empirically investigate how various enablers can contribute to I4.0-enabled CE for AFSCs. Our findings differ from those of previous studies, indicating that successful deployment of I4.0 technologies to achieve CE depends on the collective efforts of environmental, supply chain, organizational, and individual enablers. Amongst these, a hierarchical cultural environment acts as the "lubricant" linking these four levels to achieve synergies. This study breaks new ground by categorizing 27 enablers into four categories and ranking them using a GFAHP with inputs sourced from 10 decision makers.

7.1. Limitations and future research directions

We adopted a rigorous research methodology to analyze enablers of I4.0 technology adoption to achieve CE in AFSCs. However, like many other studies, our study has limitations.

The first is generalizability. Because we conducted our research in China, we considered unique features such as the country's hierarchical cultural value orientation, its aging rural and farm populations, and financial support from governments. This poses challenges for applying the results to a broader group of countries or situations. To tackle this limitation, future research in other countries might use questionnaires or case studies.

Second, we adopted a GFAHP involving ten decision makers to prioritize our enablers. Involving multiple experts and applying fuzzy set theory enhanced the accuracy of our prioritization results. However, using other MCDM techniques might extend our understanding. Future studies might analyze the topic by combining GFAHP with the group-based fuzzy technique for order preference by similarity to ideal solution (GFTOPSIS). We suggest these two techniques because they are widely used to prioritize decision-making problems, and their combination can produce synergies, for example, using GFAHP to structure a problem hierarchically and GFTOPSIS to rank alternatives.

Third, we collected data from various AFSC stakeholders, including farmers, agri-food research institutions, regional agricultural and rural governments, and agricultural technology manufacturers. Collecting data from a wide range of stakeholders leads to diverse thinking and elicits understanding of the issue from different perspectives, but makes it difficult to generate deep insights into I4.0 technologies used by specific AFSC stakeholders. To solve this limitation, future studies might conduct targeted interviews with specific groups, such as farmers, to understand what motivates them to use I4.0 technologies in their farm management.

Finally, we did not analyze barriers to I4.0 technology adoption to achieve CE. Thus, interviews might be conducted with AFSC practitioners to understand what impedes their adoption, and potential measures to mitigate these barriers. These findings might have wide impacts and contribute to I4.0 technology adoption.

CRediT authorship contribution statement

Guoqing Zhao: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Chenhui Ye:** Writing – review & editing, Formal analysis, Data curation. **Nasiru Zubairu:** Writing – review & editing, Funding acquisition. **Kaliyan Mathiyazhagan:** Writing – review & editing. **Xiongyong Zhou:** Writing – review & editing.

Declaration of competing interest

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

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Appendix 1. Interview guide

A. Introductory questions

I. Interviewee information
  - What is your current designation?
  - Can you give me a brief overview of your job within the company operations?
  - How many years have you been working in this company?
  - How many years have you been working for the agri-food industry?

II. Company information
  - Can you give me a brief overview of the company structure and its operations?
  - How many employees are working for the company?

B. Main Industry 4.0 technologies applied in the agricultural sector

- What kind of Industry 4.0 technologies have been applied in China's agricultural sector?
- What are the main difficulties or challenges in adopting these Industry 4.0 technologies?
- What measures have been adopted to tackle difficulties and also enhance the technology acceptance level among agri-food supply chain practitioners?

C. Transition to a circular economy by adopting Industry 4.0 technologies

- What are the benefits of applying Industry 4.0 technologies to achieve a circular economy of the agri-food industry?
- How would you describe the measures adopted to facilitate the adoption of Industry 4.0 technologies to achieve a circular economy of the agri-food industry?
- Do you have any suggestions that can facilitate the transitions to circular agriculture by applying Industry 4.0 technologies?

Appendix 2. Fuzzy scale of relative importance

Importance	Fuzzy scale of relative importance
Equal importance	(1,1,1)
Moderate importance	(2,3,4)
Strong importance	(4,5,6)
Very strong importance	(6,7,8)
Extremely strong importance	(8,9,9)
Intermediate values	(1,2,3), (3,4,5), (5,6,7), (7,8,9)
Values for inverse comparison	(1/3,1/2,1/1) … (1/9,1/9,1/8)

Appendix 3. Weighting of each decision maker

	CR1	CR2	CR3	CR4	Average CR	Weight of DM
DM1	0.047635	0.008593	0.08952636	0.062909361	0.052166	10.62%
DM2	0.05177	0.041968	0.06252233	0.057629427	0.053472	10.88%
DM3	0.044457	0.086849	0.09911335	0.056659638	0.07177	14.61%
DM4	0.000279	0.030391	0.08522422	0.083573227	0.049867	10.15%
DM5	0.000279	0.024455	0.08208192	0.088769505	0.048896	9.95%
DM6	0.020768	0.041451	0.09474366	0.042486206	0.049862	10.15%
DM7	0.011557	0.002497	0.10192536	0.086329741	0.050577	10.29%
DM8	0.01076	0.011557	0.0906807	0.033746331	0.036686	7.47%
DM9	0.005701	0.000279	0.07693312	0.048423046	0.032834	6.68%
DM10	0.011557	0.045149	0.09458843	0.029388669	0.045171	9.19%

Data availability

Data will be made available on request.

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