Journal of Agribusiness in Developing and Emerging Economies

Harnessing Industry 4.0 in agri supply chains: a strategy for enhanced sustainability

Harshad Sonar
Department of Operations Management, Indian Institute of Management Sambalpur, Sambalpur, India
Prasad Joshi
Symbiosis Institute of Operations Management, Symbiosis International University, Nashik, India
Nikhil Ghag
Indian Institute of Management Mumbai, Mumbai, India
Shashank Kumar
Department of Operations Management and Quantitative Techniques, Indian Institute of Management Bodh Gaya, Bodh Gaya, India, and
Nabanit Giri
Symbiosis Institute of Operations Management, Symbiosis International University, Nashik, India

Received 19 March 2025
Revised 9 September 2025
Accepted 26 October 2025

Abstract

Purpose – To investigate the underlying factors contributing to this challenge, this research aims to identify key barriers to Industry 4.0 (I4.0) adoption in agriculture supply chains to enhance sustainability. Additionally, this work seeks to develop a structured framework to examine their interactions to investigate the fundamental causes of this problem.

Design/methodology/approach – Initial identification of I4.0 adoption barriers in agricultural supply chains is done using a comprehensive literature review. The Fuzzy-Delphi method is then used for validation and finalization. Then, the Decision-Making Trial and Evaluation Laboratory approach is used to determine causal links between these barriers.

Findings – The results show that the biggest obstacles to I4.0 implementation in agricultural supply chains are "lack of management commitment," "lack of prioritization of circular economy (CE) practices," "lack of a skilled workforce" and "lack of government support."

Research limitations/implications – The study is directed from the viewpoint of a developing economy because the most pressing sustainability issues are found in these nations. I4.0 technologies will be essential in supplying developing nations with wholesome, secure, and environmentally sound food.

Originality/value – This paper offers a framework that tackles several problems in one model. As part of the technique, a thorough literature analysis is conducted to identify the main difficulties. These are then confirmed by speaking with industry experts and visiting different stakeholders in the sector. The developed framework provides an organized approach for implementing I4.0 and circular economy principles in the agricultural supply chain while methodically removing or minimizing the effects of barriers.

Keywords Industry 4.0, Sustainability, Agri supply chain, DEMATEL, Fuzzy-Delphi

Paper type Research article

1. Introduction

At the start of the 21st century, the fourth industrial revolution significantly altered the consumption of commodities and services. This revolution, known as Industry 4.0, replaced the traditional methods with a technological paradigm shift (Schöggl *et al.*, 2023). Consequently, the adoption of I4.0 resulted in massive improvements in supply chain

Statements and declarations: The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Journal of Agribusiness in Developing and Emerging Economies
© Emerald Publishing Limited
e-ISSN: 2044-0847
p-ISSN: 2044-0839
DOI 10.1108/JADEE-03-2025-0117

Downloaded from http://www.emerald.com/jadee/article-pdf/doi/10.1108/JADEE-03-2025-0117/10837281/jadee-03-2025-0117en.pdf by Institut Latihan Statistik Malaysia user on 02 Dec

management across many industries, with notable improvements in agility, efficiency, and transparency of the supply chain operations, which is vital for long-term sustainability (Amjad *et al*., 2021; Mastos *et al*., 2020; Kaleli, 2025). Organizations have managed to minimize their costs, simplify their processes, and enhance their capacity to adapt in this uncertain environment and demand volatility (Cagliano and Canterino, 2022; Kumar *et al*., 2020a, b). Digitalization enables organizations to reduce their labor and material expenses, shorten processing as well as setup times (Garay-Rondero *et al*., 2020; Martens and Zscheischler, 2022). The efficiency and effectiveness of human-machine operations, as well as their digitalization, have improved a lot with the inclusion of digital technologies (Mohapatra *et al*., 2025), which allow them to tailor themselves for meeting the demands of customers. Consequently, organizations can manufacture more through optimal utilization of resources to enhance their profitability as well as sustainability (Gadekar *et al*., 2022; Toktaş-Palut, 2022).

The agriculture sector, being one of the oldest and most crucial industries of the economy, has also begun to adopt I4.0 technologies in order to enhance its supply chain management (Latino *et al*., 2021; Shen *et al*., 2022). The agriculture sector is experiencing some challenges, like the growing demand for food, global warming, and the requirements of sustainable production practices. This digital revolution offers the chance to solve these problems in order to increase agricultural supply chain productivity, efficiency, and sustainability (Kamble and Gunasekaran, 2020; Mendes *et al*., 2022). The integration of I4.0 in the Agri supply chain management is becoming increasingly vital, which will transform food production and delivery (Patidar and Agrawal, 2020). By enabling I4.0 into every step of Agri supply chains, i.e. farm to fork, it can enhance its efficiency and sustainability, resulting in a more sustainable food system (Kumar *et al*., 2021; Latino *et al*., 2022). The adoption of I4.0 in the agri-food industry can enhance real-time visibility, agri-food procurement, inter-organizational systems, and inventory management. The Agri-food sector may enhance the coordination of technological systems through the use of cutting-edge technologies. Kumar *et al*. (2020a, b) discussed that real-time visibility and information sharing will increase flexibility and coordination to become self-aware and self-learning machines (Jayashree *et al*., 2022). For example, Smart farming sensors are used to acquire vast amounts of data. The sensor collects data that is broken down and indicates weather conditions, soil quality, yield development progress, or directs well-being. This information will be beneficial for running an agricultural food industry.

The agricultural sector is facing many issues, despite the availability of digital technologies and the benefits that they have by adopting I4.0 into the Agri supply chain. About 40% of the food produced is wasted across the entire food supply chain, as reported by the *United Nations Food and Agriculture Organization (FAO)* (Mishra and Satapathy, 2021; Lagarda-Leyva *et al*., 2019). Food loss is a significant issue in both developed and developing nations. In developing nations, poor logistics infrastructure and supply chain management practices, limited use of technology, and low investment in food production systems contribute to food loss (Rolandi *et al*., 2021; Sharma *et al*., 2024). In contrast, developed nations experience a substantial amount of food loss during the marketing and consumption stages. The perishability of food products and knowledge asymmetry between stakeholders also contribute to food fraud.

As per the report from the Government of India, one of the major issues faced by the agricultural sector in India is low yield. Developed nations' yields are 40–50% more than India's farm yields. Low agricultural production is mostly due to inadequate infrastructure, low utilization of farm technologies and best farming practices, a decline in soil fertility, and ongoing pesticide use. A farmer's cash flow and capacity to react to market variations are directly impacted by low yields in India. The existing literature (Gardas *et al*., 2019; Garske *et al*., 2021; Shen *et al*., 2022) suggests that I4.0 has the capabilities to stop excessive waste and lessen the financial burden of product recalls, outbreaks, cross-contamination, and monitor temperature variations during transport, promote transparency of food procedures, establish a smart contract, and reduce food fraud. The existing work lacks adequate support and empirical pieces of evidence for adopting I4.0 into ASCs. Furthermore, no previous studies have focused

Downloaded from http://www.emerald.com/jadee/article-pdf/doi/10.1108/JADEE-03-2025-0117/10837281/jadee-03-2025-0117en.pdf by Institut Latihan Statistik Malaysia user on 02 Dec

on barriers to implementation in the agriculture sector in a developing economy context. This study aims to address the following research questions:

RQ1. What are the significant barriers preventing the adoption of Industry 4.0 in the Agri supply chains (ASCs)?

RQ2. What is the causal relationship, and how can barriers be addressed to accelerate the implementation of these I4.0 technologies?

To answer the above questions, the following research objectives were developed.

RO1. To identify and analyze the significant barriers to the adoption of Industry 4.0 from past literature.

RO2. To develop and study the causal relationship between them and suggest suitable strategies.

This study utilizes the fuzzy-Delphi and DEMATEL methods to achieve its research objectives, as this method is widely recognized in the field of SCM for its ability to identify cause-and-effect relationships among various factors. The remaining work is organized as follows: the background of the study is discussed in Section 2, followed by research methodology and data analysis in Section 3. The results are presented in section 4, followed by a discussion of the paper in section 5, and the conclusion is summarized in section 6.

2. Literature review

Industry 4.0 has redefined how businesses design, produce, and market goods by integrating digital technologies and strengthening human–technology interactions. Bernhardt *et al*. (2021) showed that principles of industrial digitalization can be adapted to agriculture with structural modifications, while Latino *et al*. (2021) argued that Agriculture 4.0 can address global challenges such as food security, population growth, and climate change. Both highlight the potential of digitalization but differ in focus: Bernhardt *et al*. emphasize sectoral adaptation, whereas Latino *et al*. stress sustainability outcomes. Technologies such as IoT, robotics, GPS, and GIS have accelerated this transition, yet most studies remain conceptual and technology-focused. Limited attention has been paid to adoption barriers such as infrastructure gaps, governance issues, and farmers' digital readiness, creating a critical gap in understanding how Industry 4.0 can be effectively implemented in agricultural supply chains.

More recent scholarly work has highlighted the disruptive impact of Industry 4.0 technologies on agricultural supply chains (ASCs), with blockchain, artificial intelligence (AI), machine learning (ML), and digitalization being the prominent topics. Yadav *et al*. (2024) progressed this conversation by proposing a blockchain-based framework to facilitate net-zero approaches in agri-food supply chains and illustrating its promise to improve traceability, transparency, and carbon footprint minimization. But the authors also cautioned that high costs of implementation, poor infrastructure, and a lack of regulatory mechanisms remain to hinder its large-scale adoption. Also, e-enabled ASCs found energy-intensive activities, ignorance among farmers, data privacy issues, and intermediary resistance to be key barriers to blockchain adoption, with government incentives, subsidies, and capacity-building interventions being key enablers. Pursuing this line of research, Rajendran *et al*. (2025) proposed the term "enerchainability" to connect blockchain uptake with energy efficiency and green performance. Their research indicated that younger and more educated farmers tend to adopt blockchain systems, but issues of digital illiteracy, expense, and declining bargaining power for smallholders remain. In addition to blockchain, empirical research has emphasized the general contribution of Industry 4.0 capabilities like IoT, big data, and AI to improved ASC performance. Empirical research showed that these digital capabilities have a positive impact on ASC integration, which in turn mediates enhanced sustainability outcomes. However, constraints like limited investment, fragmented infrastructure, and shortages in qualified staff

Downloaded from http://www.emerald.com/jadee/article-pdf/doi/10.1108/JADEE-03-2025-0117/10837281/jadee-03-2025-0117en.pdf by Institut Latihan Statistik Malaysia user on 02 Dec

decrease the general impact of such interventions. Similarly, Nayal *et al*. (2023) evaluated the adoption of AI and ML to address COVID-19 disruptions in ASCs and concluded that, while the two advanced forecasting, resource optimization, and resilience, adoption was limited by deficiencies in regulations, poor data security frameworks, and low digital literacy across stakeholders. The COVID-19 pandemic also spurred research on supply chain resilience in the agricultural sector. Kumari *et al*. (2023) identified leadership commitment, digitalization, cross-functional coordination, and supplier relationship management as key antecedents of ASC performance in emerging economies, though barriers such as labor shortages, demand fluctuations, and ICT gaps significantly constrained outcomes.

Lioutas *et al*. (2021) applied the artificial trolley dilemma framework to analyze how digitalization affects environmental, social, cultural, and political dimensions of food safety, while Shen *et al*. (2022) demonstrated, using green productivity indicators and data envelopment analysis, that Internet development fosters green growth and sustainable development. Ingram and Maye (2020) further highlighted how digitalization reshapes agricultural knowledge systems, creating opportunities for decision-makers and advisors. Together, these studies suggest that digitalization can drive sustainability, though largely at a conceptual level with limited empirical grounding. At the same time, much research work has documented distributional and structural challenges. Rolandi *et al*. (2021) found that digitalization benefits rural development but risks widening inequalities, as wealthier farmers are more likely to access advanced technologies. Similar concerns appear in Aamer *et al*. (2021), who identified 15 IoT adoption challenges in food supply chains, and Goller *et al*. (2021), who showed that knowledge gaps among dairy farmers in Germany hinder digital adoption. Kumar *et al*. (2021) extended this discussion to Industry 4.0–circular economy integration, reporting that the absence of government policies and protocols remains a major barrier. Likewise, Lovkova *et al*. (2022) identified four critical constraints in Russia: financial limitations, skills shortages, weak infrastructure, and legal inadequacies, while Prause (2021) cautioned that digitalization can reduce labor autonomy through surveillance. These contrasting findings underscore that while efficiency gains are acknowledged, adoption barriers remain systemic and context-specific.

Recent research has also explored governance and institutional perspectives. Qin *et al*. (2022) proposed an analytical framework emphasizing the role of digital platforms and farmer behavior in adoption, while Ciruela-Lorenzo *et al*. (2020) argued for cooperatives as conduits for digital transition. Governance-related risks are further evidenced in the European context, where Garske *et al*. (2021) and Martens and Zscheischler (2022) highlighted weaknesses in data security, product safety, and regulatory clarity, as well as broader controversies surrounding data privacy and inequality. Collectively, these studies demonstrate that governance gaps persist across regions, but few works connect these to long-term sustainability outcomes. The COVID-19 pandemic provided a context to test the resilience of digitalization. Fang and Zhang (2021) reported that digital financial inclusion directly increased agricultural trade during the pandemic, while Haggag (2021) identified digitalization as a mitigation tool against supply chain disruptions. Similarly, Akzar *et al*. (2025) emphasized digitalization as a key strategy to meet sustainability, climate, and biodiversity goals. However, despite these insights, critical challenges, including inadequate policies (Qin *et al*., 2022), socio-ethical and ecological issues (Lioutas *et al*., 2021), and persistent governance fragmentation (Martens and Zscheischler, 2022), remain insufficiently addressed. The issues also include unskilled workers adopting digital tools, reduction of biodiversity, confidentiality of farm data, degradation of resources, and the technofication of agriculture. The study also suggests that digitalization in agriculture presents a "trolley dilemma," where the potential for greater food production through technology has not been able to address food shortages caused by a growing population. The brief of the literature review and papers referred to are listed in Table 1.

Although several studies have explored the role of Industry 4.0 in agriculture, many have only partially addressed the barriers constraining its adoption. Kumar *et al*. (2021) identified

Downloaded from http://www.emerald.com/jadee/article-pdf/doi/10.1108/JADEE-03-2025-0117/10837281/jadee-03-2025-0117en.pdf by Institut Latihan Statistik Malaysia user on 02 Dec

Table 1. List of existing studies on Industry 4.0 in Agri supply chains

Author(s)	Focus	Methodology	Key findings
Yadav *et al.* (2024)	Blockchain for net-zero strategies	Conceptual framework	Blockchain reduces carbon footprint, improves traceability; barriers: high costs, lack of infrastructure, weak regulations
Sharma *et al.* (2022)	Impact of I4.0 capabilities on ASC	Empirical survey + SEM	I4.0 capabilities, sustainable performance, low investment, skill gaps, infrastructure
Zkik *et al.* (2023)	Blockchain adoption barriers and enablers	Mixed-methods	energy costs, privacy concerns, farmer awareness, intermediary resistance; Enablers: policies, subsidies, training
Sharma *et al.* (2024)	Risks and mitigation strategies	Case study + thematic analysis	Risks: labor shortages, logistics disruptions, demand shocks; Mitigation: ICT, local sourcing, resilience planning
Rajendran *et al.* (2025)	Blockchain adoption and energy efficiency	Farmer survey + UTAUT	Adoption driven by young/educated farmers; barriers: cost, digital illiteracy, bargaining power issues
Kumari *et al.* (2023)	Antecedents of ASC performance	Empirical survey + SEM	Drivers: leadership, digitalization, coordination, supplier ties; barriers: labor shortages, demand imbalance, ICT weakness
Nayal *et al.* (2023)	AI/ML for disruption management	Delphi–ISM–Fuzzy–MICMAC–ANP	AI/ML aids forecasting, resource use, resilience; barriers: poor regulation, data security, digital literacy
Bernhardt *et al.* (2021)	Applicability of digitalization principles to agriculture	Conceptual/ Comparative	Industrial digitalization aspects transferable to agriculture with structural modifications
Latino *et al.* (2021)	Role of A4.0 in sustainability	Review	A4.0 enables addressing food safety, climate change, and population growth through digital innovations
Lioutas *et al.* (2021)	Socio-political dilemmas of digitalization	Analytical framework	Ethical, societal, and governance challenges
Shen *et al.* (2022)	Impact of the internet and digitalization on green growth	DEA	Digitalization improves productivity and sustainability
Ingram and Maye (2020)	Digitalization of agricultural knowledge	Qualitative	Digitalization creates new opportunities for decision-making and innovation
Rolandi *et al.* (2021)	Outcomes of agricultural digitalization	Taxonomy/Grid framework	Efficiency benefits but risk of unequal access for smallholders
Aamer *et al.* (2021)	IoT adoption challenges in FSC	Empirical	Interoperability, data security, lack of standards
Goller *et al.* (2021)	Digitalization challenges	Case study	Lack of knowledge and training hinders adoption
Kumar *et al.* (2021)	Integration of I4.0 with circular economy	MCDM	11 barriers, including lack of government support, weak policies, shortage of skills
Lovkova *et al.* (2022)	Agricultural digitalization challenges	Survey/Qualitative	Financial constraints, lack of skilled staff, inadequate infrastructure, weak legal framework
Prause (2021)	Digitalization and labor	Conceptual/Analytical	Potential negative impact on workforce and surveillance issues

(*continued*)

Downloaded from http://www.emerald.com/jadee/article-pdf/doi/10.1108/JADEE-03-2025-0117/10837281/jadee-03-2025-0117en.pdf by Institut Latihan Statistik Malaysia user on 02 Dec

Table 1. Continued

Author(s)	Focus	Methodology	Key findings
Qin *et al*. (2022)	Analytical framework for digitalization	Framework-based	Common digital platforms and hardware help, but farmer behavior is critical
Ciruela-Lorenzo *et al*. (2020)	Role of cooperatives in digitalization	Conceptual	Cooperatives can facilitate adoption and inclusivity
Fang and Zhang (2021)	Digital financial inclusion	Empirical	1% rise in financial inclusion, 1.6% increase in agricultural trade during COVID-19
Haggag (2021)	Response to pandemic	Review	Advocates digitalization as mitigation strategy
Akzar *et al*. (2025)	Digitalization for sustainability targets	Conceptual	Productivity, innovation, biodiversity protection
Garske *et al*. (2021)	Policy and legal frameworks	Policy review	Weaknesses in data security, product safety, and sustainability linkage
Martens and Scheischler (2022)	Governance controversies	Discourse analysis	Issues of data privacy, regulation, and inequality
Zhao *et al*. (2024)	Barriers to I4.0 adoption for sustainability	Fuzzy AHP	27 barriers across 6 categories: technological, economic, social, environmental, organizational, and supply chain

governance-related barriers, including a lack of policy support, but did not explore their interaction with technological and organizational challenges. Similarly, Goller *et al*. (2021) emphasized farmers' lack of knowledge and training as adoption barriers, yet did not consider how this intersects with infrastructural deficiencies. Aamer *et al*. (2021) highlighted interoperability and data security challenges in the food supply chain, but the analysis is limited to IoT adoption without extending to broader I4.0 ecosystems. Zhao *et al*. (2024) offered a barrier classification in agri-food supply chains, but empirical evidence on how these barriers influence sustainability outcomes remains scarce. Yadav *et al*. (2024) demonstrated the potential of blockchain for net-zero strategies but noted that issues such as costs and regulatory gaps were discussed in isolation from social and behavioral barriers. Similarly, Rajendran *et al*. (2025) introduced the concept of "enerchainability," yet the analysis was limited to farmers' willingness to adopt blockchain and did not extend to broader system-wide impacts. Nayal *et al*. (2023) examined AI/ML applications in mitigating COVID-19 disruptions but focused largely on technological and regulatory barriers without integrating supply chain governance challenges. Kumari *et al*. (2023) identified digitalization and leadership as drivers of resilience during COVID-19, but labor and ICT-related barriers were not linked to long-term sustainability outcomes.

In light of the discussed limitations, this study aims to provide a holistic assessment of barriers to Industry 4.0 adoption in agricultural supply chains. Unlike prior research that examined isolated technological, organizational, or policy challenges, our work develops an integrative framework that explicitly connects them to sustainability outcomes. This approach addresses the fragmentation in existing studies and offers actionable insights for advancing sustainable and resilient agri-food systems. To address the identified gap, this study categorizes barriers to Industry 4.0 adoption in agricultural supply chains and examines their linkages with sustainability outcomes. To identify barriers to Industry 4.0 adoption in agricultural supply chains, searches were conducted in Scopus and Web of Science using combinations of the keywords *"Industry 4.0," "digitalization," "barriers," "agriculture supply chain,"* and *"sustainability."* To ensure rigor, only peer-reviewed journal articles published in English were included, with a focus on studies examining agricultural supply

Downloaded from http://www.emerald.com/jadee/article-pdf/doi/10.1108/JADEE-03-2025-0117/10837281/jadee-03-2025-0117en.pdf by Institut Latihan Statistik Malaysia user on 02 Dec

chains, agri-food systems, or related digitalization contexts that explicitly reported barriers, enablers, or sustainability implications. Studies were excluded if they were conference papers, book chapters, reports, or non-scholarly sources, or if they addressed Industry 4.0 solely in manufacturing or other non-agricultural sectors without a clear linkage to agriculture. Similarly, articles discussing agricultural digitalization without reference to adoption barriers or sustainability outcomes were not considered. Titles and abstracts were screened for relevance, followed by full-text reviews of shortlisted articles. The consolidated list of barriers is presented in Table 2.

3. Research methodology

The purpose of this study is to identify and evaluate crucial barriers to I4.0 adoption in ASCs. From the literature, initially, 11 barriers have been identified and validated by the experts using the fuzzy-Delphi method. Finalized barriers are then ranked and prioritized using the DEMATEL method. Initially, a list of organizations was identified from the snowball sampling technique. Experts from these organizations for this study have been contacted by email. Out of thirteen experts, 3 experts rejected our request, and finally, ten experts participated in this study. All experts have a minimum of seven years of experience in Agri supply chains. These experts are involved in managing various activities related to the supply chain, i.e. logistics, packaging, inventory control, warehouse operations, etc. The judgments are aggregated using the consensus method. Table 3 summarizes the experts who participated in this study. The participating companies represent diverse sectors within the agribusiness and allied industries, located primarily in the western region of India. All experts hold senior or managerial positions such as CEOs, supply chain managers, operations managers, and inventory heads, with professional experience ranging from 7 to 20 years. These organizations are actively engaged in logistics, warehousing, inventory control, and distribution operations. The inclusion of such experienced top and middle-level managers ensures that the insights gathered reflect practical, industry-based perspectives on agricultural supply chain management.

3.1 Fuzzy Delphi method

Given its features of integrating expert knowledge, participant anonymity, and regular feedback, the Delphi approach is very helpful in identifying the evaluation indicators. To determine the evaluation indicators, this study also uses the Delphi technique. However, the conventional Delphi approach has glaring flaws, including subjectivity and time-consuming characteristics. The FDM combination allows a comprehensive depiction of expert judgments with a smaller sample size. Additionally, it benefited by reducing the costs and length of investigations. Fuzzy numbers are used in this method to reflect the expert opinions. Then, using a fuzzy process, the subjective judgments are changed into objective data. The fuzzy Delphi approach has the following primary advantages over the conventional technique: (a) it fully considers the ambiguity and uncertainty of the experts' subjective reasoning, allowing for full consideration of each expert's opinion in the decision. As a result, the outcomes are fair and unbiased. (b) By obtaining the conclusion through just one round of surveying, the classic Delphi method's multiple rounds of surveying are avoided. Thus, time and money spent on research are cut. For the detailed steps of this method, please refer to Ishikawa *et al*. (1993), Liang *et al*. (2022). The 9-point Likert scale is used, having a threshold value of 5.6, as stated by Zhang (2017). The methodological flowchart is presented in Figure 1 below. The defuzzified values obtained through the Fuzzy Delphi process (Table 4) represent the final validated set of barriers, which are subsequently used as the input for the DEMATEL analysis to identify the causal and effect relationships among these barriers. Table 4 represents the aggregate fuzzy judgments for all the barriers. The barriers having a defuzzification score less than 5.6 are excluded from further analysis.

Downloaded from http://www.emerald.com/jadee/article-pdf/doi/10.1108/JADEE-03-2025-0117/10837281/jadee-03-2025-0117en.pdf by Institut Latihan Statistik Malaysia user on 02 Dec

Table 2. List of barriers to Industry 4.0 in Agri supply chains (ASCs)

Sr. No.	Barriers	Description	References
1	Lack of digital environment	Many ASCs limit their ability to leverage Industry 4.0 technologies due to the absence of a robust digital infrastructure. Without such a digital backbone, it is challenging to analyze real-time data affecting its efficiency and visibility. This lack of a digital environment prevents seamless integration across stages of the supply chain, impeding efforts to optimize resources, reduce waste, and implement sustainable practices effectively	Akbari *et al.* (2023), Zhao *et al.* (2024)
2	Lack of management commitment	Lack of commitment from top managers to driving digital and sustainable transformations, due to short-term profitability concerns or limited understanding of long-term benefits. This barrier creates a top-down effect, where employees may also feel unmotivated or unsupported in embracing digital tools and sustainability in their day-to-day operations	Ciruela-Lorenzo *et al.* (2020), Mogale *et al.* (2023), Zhao *et al.* (2024)
3	Lack of sustainable practices	Unless sustainability is integrated into core operations, businesses lose opportunities to save resources, minimize waste, and save costs, which are essential in ASC. Lack of sustainability leads to conventional, linear operations that depend considerably on non-renewable materials and have negative impacts on the environment. This disconnect renders it difficult to implement circular economy practices, which are required to develop a greener and more sustainable supply chain	Ali and Phan (2022)
4	Lack of eco-design aspect	Eco-design plays a key role in reducing environmental footprints across the lifecycle of a product, but it remains neglected in ASC. By neglecting to incorporate eco-friendly designs, businesses do not take into account energy efficiency, recyclability, and minimized waste in product development and packaging. This absence of eco-design translates into lost opportunities for sustainable innovation and minimized lifecycle emissions, foiling attempts to bring supply chains into alignment with environmental objectives	Kumar *et al.* (2021), Mogale *et al.* (2023)
5	Fear of cultural change	The transition to Industry 4.0 also involves, in many cases, substantial cultural adjustment, which can trigger resistance among employees and stakeholders who are used to established ways of working. Concern about job loss, lack of knowledge of new technology, and anxiety toward change can inhibit the uptake of digital technologies. Breaking through this resistance is essential, as adopting new styles of working facilitates the change required for sustainability and efficiency gains across the ASC.	Sarkar *et al.* (2025), Verza *et al.* (2025)

(*continued*)

Downloaded from http://www.emerald.com/jadee/article-pdf/doi/10.1108/JADEE-03-2025-0117/10837281/jadee-03-2025-0117en.pdf by Institut Latihan Statistik Malaysia user on 02 Dec

Table 2. Continued

Sr. No.	Barriers	Description	References
6	Lack of priorities to CE practices	Circular economy (CE) strategies, including recycling, reuse, and minimizing waste, are key to establishing a sustainable supply chain. These strategies, however, do not always take priority in organizational plans. Without prioritizing CE strategies, it is difficult to enact sustainable resource management strategies, which restricts the ability to decrease environmental footprint and increase long-term resilience	Chavhan and Dutta (2025)
7	Lack of skilled workforce	Implementation of Industry 4.0 technologies demands a qualified workforce with the skills in digital tools, data analysis, and sustainable operations. Yet, trained professionals are generally lacking in ASC who can spearhead these initiatives. The lack of such skills leads to ineffective use of digital solutions, which hinders the possibility of achieving sustainability objectives as well as achieving process efficiency along the supply chain	Haider *et al.* (2024), Latino *et al.* (2021)
8	Lack of government support and incentives	Government incentives and policies have a serious impact in promoting the use of sustainable and digital practices. In the absence of strong government support in terms of grants or tax credits, businesses cannot afford to invest in the initial expenses involved in such changes. This insufficiency of government support can deter investment in green practices and sophisticated technologies, hindering the transition towards a sustainable ASC.	Jain *et al.* (2025), Kumar *et al.* (2020a, b)
9	Governance of digital transformation	Effective digital transformation needs well-defined governance structures to lead implementation, harmonize stakeholders, and track performance. Ineffective governance frameworks yield disconnected or irregular efforts, minimizing the impact of Industry 4.0 initiatives. Lacking coordinated management, the convergence of digital solutions is difficult, and the overall alignment of sustainability objectives in the supply chain is hindered	Ali and Phan (2022), Sonar *et al.* (2024a, b)
10	Lack of infrastructure	Successful deployment of digital technologies in ASC necessitates strong infrastructure, such as stable internet connectivity, power supply, and sophisticated machinery. In most areas, poor infrastructure restricts the scope for automation, data exchange, and other digital interventions. This absence of foundational infrastructure is one of the main obstacles to the full deployment of Industry 4.0 and ensuring sustainable operations in agriculture	Liu *et al.* (2021), Sarkar *et al.* (2025)

(*continued*)

Downloaded from http://www.emerald.com/jadee/article-pdf/doi/10.1108/JADEE-03-2025-0117/10837281/jadee-03-2025-0117en.pdf by Institut Latihan Statistik Malaysia user on 02 Dec

Table 2. Continued

Sr. No.	Barriers	Description	References
11	Legal and technical challenges	Regulatory compliance, data privacy issues, and technical interoperability problems are major challenges in digital transformation initiatives. Legal barriers may delay the uptake of digital tools, whereas technical challenges such as non-standardization make it difficult for data to be exchanged between systems. Combined, these challenges present barriers to putting digital solutions in place and scaling up, which are needed to make ASC efficient and sustainable	Rolandi *et al.* (2021), Sharma *et al.* (2024), Sonar *et al.* (2024a, b)

Table 3. Summary of Experts who participated in a study

Sr. No.	Company	Designation of expert	Experience in years
1	AHS	CEO	12
2	CSG	Assistant Manager-Inventory	10
3	BFG	Manager	9
4	NHU	CEO	14
5	FGJ	Supply Chain Manager	8
6	REL	Operations Manager	7
7	YIL	Assistant Manager	9
8	EXU	Supervisor-Logistics	7
9	KUL	Head-Dispatch	11
10	BFR-ERT	CEO	20

3.2 DEMATEL method

Amongst Several multi-criteria decision-making (MCDM) methods for analyzing the criteria, DEMATEL analysis builds a causal relationship among all the factors. This MCDM approach is used to analyze complex problems (Uygun *et al*., 2014), which primarily aids in analyzing the contributing factors to issues within the context of cause-effect groups (Malekzadeh *et al*., 2016). The above-mentioned grouping of factors enables business executives and researchers to visualize their behavior (Ghaemi Rad *et al*., 2018). This approach helps researchers understand the contextual and structural relationships along with the strengths as compared to other MCDM techniques such as analytical network process (ANP), total interpretive structural modeling (TISM), and graph theory and matrix approach (GTMA), etc.) (Gwo-Hshiung *et al*., 2011). In DEMATEL, we assume that all criteria are mutually dependent and influence other criteria. This MCDM tool uses a weighting procedure to determine the significance of the criteria. A direct-influence graph is used in DEMATEL analysis to represent relationships among the factors. Each node symbolizes that each factor has been analyzed, and the arc between the nodes symbolizes the impact and intensity of the factors. The intensity of each factor is assigned with some values ranging from 0 to 4. Please refer to Kamble and Gunasekaran (2020) for detailed steps involved in the DEMATEL method.

4. Result

The results of this study provide a comprehensive evaluation of the barriers hindering Industry 4.0 adoption in agricultural supply chains. Based on expert judgments and subsequent

Downloaded from http://www.emerald.com/jadee/article-pdf/doi/10.1108/JADEE-03-2025-0117/10837281/jadee-03-2025-0117en.pdf by Institut Latihan Statistik Malaysia user on 02 Dec

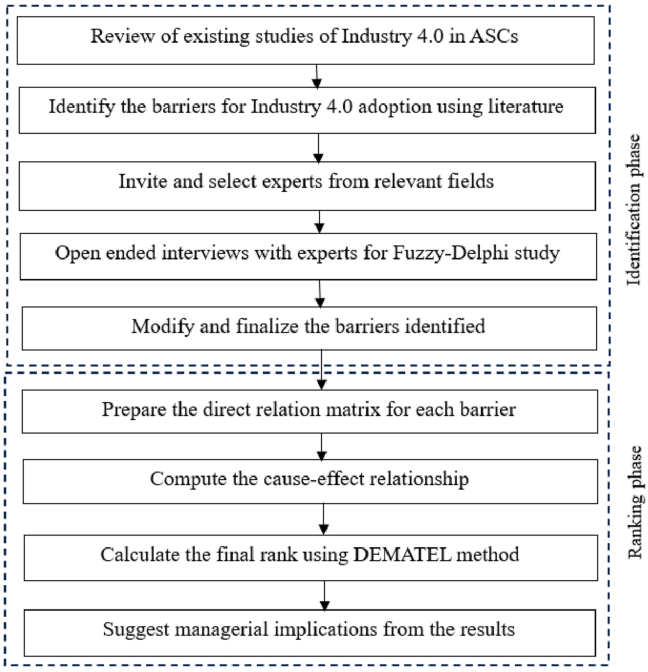

Figure 1. Methodological flowchart

Table 4. Aggregate fuzzy judgments

Barriers	Scores		Geometric mean	Aggregate fuzzy number	Final (defuzzification)
	Min	Max			
Lack of digital environment (LDE)	3	9	6.568	3,9, 6.568	6.189
Lack of management commitment (LMC)	3	9	5.869	1,9, 5.869	5.956
Lack of sustainable practices (LSP)	3	9	6.745	1,9, 6.745	6.248
Lack of eco-design aspect (LED)	3	9	6.213	3,9, 6.213	6.071
Fear of cultural change (FCC)	1	9	6.895	1,9, 6.895	5.631
Lack of priorities to CE practices (LCE)	3	9	5.256	3,9, 5.256	5.752
Lack of skilled workforce (LSW)	3	9	6.125	3,9, 6.125	6.042
Lack of government support and incentives (LGS)	3	9	6.132	1,9, 6.132	6.327
Governance of digital transformation (GDT)	3	9	4.563	3,9, 4.563	5.521
Lack of infrastructure (LIF)	3	9	5.0256	3,9, 5.0256	5.675
Legal and technical challenges (LTC)	1	9	4.987	1,9, 4.987	4.995

application of the Fuzzy Delphi method, the finalized barriers were validated and prioritized for further analysis. The DEMATEL approach was then employed to examine the interdependencies and causal relationships among these barriers, thereby identifying those that exert the strongest influence on others. This systematic analysis not only highlights the most critical obstacles but also clarifies how they interact within the broader ecosystem of agricultural supply chains. Presenting these results through structured tables allows for clear

Downloaded from http://www.emerald.com/jadee/article-pdf/doi/10.1108/JADEE-03-2025-0117/10837281/jadee-03-2025-0117en.pdf by Institut Latihan Statistik Malaysia user on 02 Dec

interpretation of expert insights and offers a robust foundation for deriving managerial and policy implications.

The analysis begins with the construction of the direct relation matrix, which records the initial influence scores assigned by experts for each barrier. This matrix was then normalized to ensure comparability across factors, and the total relation matrix was generated to capture both direct and indirect effects. These steps provide the foundation for determining the prominence and net influence of each barrier, which are further illustrated through the causal-effect analysis and corresponding diagram in the subsequent results. Table 5 depicts the direct relationship matrix after the consensus from expert judgments.

The direct-relation matrix is normalized by dividing each element by the maximum row sum. For example, the first row total is 16, obtained from the summation of 0 + 3+3 + 2+1 + 2+2 + 1+2. The highest row sum in the matrix is 18, which is used as the normalization denominator. Accordingly, each element of the matrix is divided by 18 to generate the normalized direct-relation matrix presented in Table 6. The total relationship matrix is obtained to get D and R values using MATLAB software version R2022, as shown in Table 7.

An inter-relation matrix was constructed to evaluate the impact of various factors on each other, with the D and R values indicating cause-and-effect relationships. The D + R column provides information about the significance of the criteria and the extent of their relationships with other criteria. Criteria with higher D + R values are considered more important and have stronger relationships with other criteria. Lack of management commitment was found to be the most important criterion, having a larger D + R value, indicating a strong relationship with other criteria (Table 8). D-R values represent the type of relationship between criteria, with positive values indicating a cause-and-effect relationship and negative values indicating an effect-cause relationship. These values are influenced by other criteria in the matrix. A scatter plot in Excel is utilized to create a causal diagram, where D + R and D-R values are plotted on the horizontal and vertical axes, respectively. Figure 2 provides a visual representation of the inter-relationship between criteria. Overall, the results reveal that "Lack of management commitment," "Lack of prioritization of circular economy practices," "Lack of skilled workforce," and "Lack of government support and incentives" emerge as the most critical barriers, exerting substantial influence on other challenges within the system. The causal analysis distinguishes between cause-group barriers, such as infrastructure, governance, and cultural factors, and effect-group barriers, such as management commitment and sustainable practices. This structured mapping of interdependencies offers a clear hierarchy of obstacles, setting the stage for deeper interpretation in the discussion section.

5. Discussion

This study analyzed the association between barriers in the agriculture supply chain (ASC) based on expert judgments. The DEMATEL approach was employed to illustrate the results in

Table 5. Direct relationship matrix

Factors	LDE	LMC	LSP	LED	FCC	LCE	LSW	LGS	LIF
LDE	0	3	3	2	1	2	2	1	2
LMC	1	0	4	3	1	3	2	1	1
LSP	1	2	0	3	1	3	1	2	1
LED	1	4	3	0	1	3	1	1	2
FCC	1	3	1	1	0	1	3	1	1
LCE	1	3	3	3	1	0	1	1	3
LSW	2	3	2	3	1	2	0	1	1
LGS	2	2	2	2	2	3	2	0	3
LIF	2	2	2	3	1	3	1	2	0

Downloaded from http://www.emerald.com/jadee/article-pdf/doi/10.1108/JADEE-03-2025-0117/10837281/jadee-03-2025-0117en.pdf by Institut Latihan Statistik Malaysia user on 02 Dec

Table 6. Normalized direct relation matrix

Factors	LDE	LMC	LSP	LED	FCC	LCE	LSW	LGS	LIF
LDE	0.000	0.167	0.167	0.111	0.056	0.111	0.111	0.056	0.111
LMC	0.056	0.000	0.222	0.167	0.056	0.167	0.111	0.056	0.056
LSP	0.056	0.111	0.000	0.167	0.056	0.167	0.056	0.111	0.056
LED	0.056	0.222	0.167	0.000	0.056	0.167	0.056	0.056	0.111
FCC	0.056	0.167	0.056	0.056	0.000	0.056	0.167	0.056	0.056
LCE	0.056	0.167	0.167	0.167	0.056	0.000	0.056	0.056	0.167
LSW	0.111	0.167	0.111	0.167	0.056	0.111	0.000	0.056	0.056
LGS	0.111	0.111	0.111	0.111	0.111	0.167	0.111	0.000	0.167
LIF	0.111	0.111	0.111	0.167	0.056	0.167	0.056	0.111	0.000

Table 7. Total-relation matrix

Factors	LDE	LMC	LSP	LED	FCC	LCE	LSW	LGS	LIF	D
LDE	0.4343	1.011	0.9935	0.9376	0.4216	0.9323	0.5932	0.483	0.6687	6.4752
LMC	0.4832	0.8665	1.0328	0.9798	0.4201	0.9747	0.5867	0.4814	0.6243	6.4495
LSP	0.4428	0.8829	0.7632	0.8949	0.3869	0.8943	0.4967	0.4836	0.5763	5.8216
LED	0.4866	1.0564	1.0009	0.8432	0.4229	0.9833	0.5478	0.4849	0.6734	6.4994
FCC	0.3888	0.8106	0.7022	0.6942	0.2828	0.6867	0.5331	0.3779	0.4844	4.9607
LCE	0.4897	1.0156	0.9983	0.9877	0.4237	0.8418	0.5467	0.4878	0.7201	6.5114
LSW	0.5096	0.9711	0.9076	0.9364	0.4021	0.8878	0.4685	0.4566	0.595	6.1347
LGS	0.5878	1.066	1.0374	1.0281	0.5128	1.0677	0.6528	0.4778	0.7875	7.2179
LIF	0.5406	0.9815	0.9598	0.9904	0.429	0.9894	0.5534	0.5339	0.5881	6.5661
R	4.3634	8.6616	8.3957	8.2923	3.7019	8.258	4.9789	4.2669	5.7178	

Table 8. Cause-effect relation

Code	Barriers	D	R	D-R	D + R	Rank	Impact
LDE	Lack of digital environment	6.4752	4.3634	2.1118	10.8386	8	Cause
LMC	Lack of management commitment	6.4495	8.6616	−2.2121	15.1111	1	Effect
LSP	Lack of sustainable practices	5.8216	8.3957	−2.5741	14.2173	4	Effect
LED	Lack of eco-design aspect	6.4994	8.2923	−1.7929	14.7917	2	Effect
FCC	Fear of cultural change	4.9607	3.7019	1.2588	8.6626	9	Cause
LCE	Lack of priorities to CE practices	6.5114	8.258	−1.7466	14.7694	3	Effect
LSW	Lack of skilled workforce	6.1347	4.9789	1.1558	11.1136	7	Cause
LGS	Lack of government support and incentives	7.2179	4.2669	2.9513	11.4848	6	Cause
LIF	Lack of infrastructure	6.5661	5.7178	0.8483	12.2839	5	Cause

a causal digraph. According to the causal relationships, the barriers that require the most immediate attention are Lack of management commitment (15.111), Lack of priorities to CE practices (14.792), Lack of government support and incentives (14.769), Lack of skilled workforce (14.217), Lack of infrastructure (12.284), Lack of digital environment (11.485), Lack of sustainable practices (11.114), Fear of cultural change (10.839), and Lack of eco-design aspect (8.663). Positive D–R values indicate that "LGS > LDE > FCC > LSW > LIF" constitute the cause-group barriers, meaning these barriers exert a greater influence on others than they receive. In contrast, negative D–R values suggest that LMC, LSP, LED, and LCE are effect-group barriers, being more heavily influenced by others. Although the discussion notes

Downloaded from http://www.emerald.com/jadee/article-pdf/doi/10.1108/JADEE-03-2025-0117/10837281/jadee-03-2025-0117en.pdf by Institut Latihan Statistik Malaysia user on 02 Dec

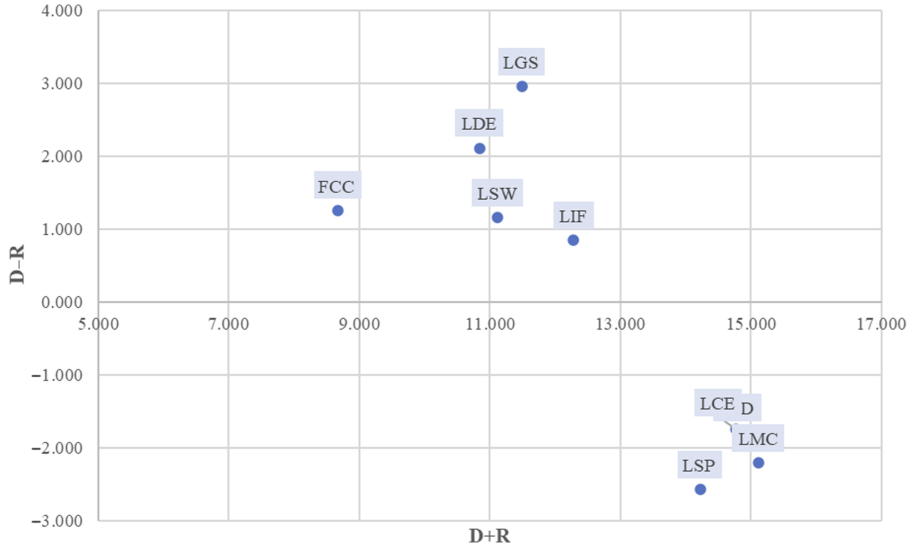

Figure 2. Causal diagram

"Lack of digital environment" as a prominent cause barrier, it is closely followed by "Fear of culture change," both significantly impacting other barriers. Among the cause-group barriers, the highest importance is attributed to "Lack of eco-design aspect," "Lack of sustainable practices," and "Lack of infrastructure."

Based on expert opinions, the current study evaluates barriers to adopting Industry 4.0 (I4.0) for long-term sustainability in ASCs. DEMATEL analysis was applied to determine the relative importance of these barriers for rapid I4.0 adoption. The research can guide managers about the consequences of these barriers to guide strategic decision-making. Managers should pay special attention to barriers with high cause-and-effect relationships while taking into account their impact on other barriers. Implementing I4.0 necessitates changing existing business models, not originally intended for sustainability and circular economy (CE), but not just digitizing processes. Strong management commitment is needed to overcome the challenges involved in the fast adoption of I4.0.

Combining CE with digital technologies like AI can enhance productivity and resource use efficiency in agri-food systems (Tseng *et al*., 2019). Shifting to CE is, however, multifaceted and encumbered by various barriers such as skills shortages, technical constraints, logistical and organizational complexities, and institutional and policy impediments (Mehmood *et al*., 2021). Thus, prioritizing CE practices is key to successful implementation. The successful design and implementation of digital technologies are also dependent on a highly competent workforce. Not many stakeholders in the agri-supply chain have the technical expertise and applied competencies to embrace sophisticated digital instruments (Lin *et al*., 2020). Overcoming this barrier can enhance I4.0 adoption and improve ASC sustainability. Muduli *et al*. (2020) underlined the necessity of a cultural transformation to upskill the current workforce, which can be enabled by means of training initiatives and the establishment of a conducive digital ecosystem.

Inadequate regulation and governance have been generally agreed to be a barrier. Encouragement of innovation, technology transfer, and eco-innovation policies by government policies promotes I4.0 adoption. In developing economies, archaic regulatory mechanisms are inhibiting an enabling business environment for the adoption of digital tools. ASC practitioners need to be offered financial incentives while embracing I4.0 and

Downloaded from http://www.emerald.com/jadee/article-pdf/doi/10.1108/JADEE-03-2025-0117/10837281/jadee-03-2025-0117en.pdf by Institut Latihan Statistik Malaysia user on 02 Dec

sustainability, since the investments are high and adopting sustainability can curtail profitability. Government assistance is also essential in creating environmental policies and monitoring systems in the ASC.

Furthermore, "Lack of infrastructure," "Lack of digital environment," and "Lack of sustainable practices" are major business-level barriers. ASC quality requires modern accountability systems, traceability and tracking technologies, and active monitoring (Verdouw *et al*., 2018). Food safety is regularly undermined by inadequate IoT adoption. The lowest-ranked barrier in I4.0 adoption is the "Lack of eco-design aspect," as other barriers are more pressing in developing economies. Nevertheless, as research and development address more critical barriers, eco-design presents a significant opportunity for future study. Increased industry participation is expected as stakeholders gain familiarity with emerging technologies.

According to the ILO (2019) report, the lack of skilled labor in 44 countries across 163 industries hinders the implementation of I4.0 and CE practices. Green agriculture and sustainability are projected to generate 7–8 million jobs by 2030, primarily driven by skill shifts in developing nations. To prepare the workforce for emerging green economies, governments should support skill development, invest in education and vocational training programs, provide financial incentives for sustainable practices, and promote industry-academia collaboration (Ajer *et al*., 2024). The adoption of I4.0 can motivate ASC practitioners to embrace sustainable practices, facilitated by the development of international standards and protocols.

In summary, this study highlights that barriers such as a lack of management commitment, inadequate prioritization of circular economy practices, a shortage of skilled workforce, and insufficient government support exert the strongest influence on Industry 4.0 adoption in agricultural supply chains. While infrastructure and digital environment remain critical business-level challenges, cultural resistance and governance gaps also amplify implementation difficulties. Addressing these barriers collectively is essential to accelerate digital transformation and enhance sustainability outcomes in the agri-food sector. These findings provide important insights not only for researchers but also for policymakers, industry managers, and cooperatives. By identifying the most influential causal barriers and distinguishing between systemic and organizational challenges, this study lays the groundwork for actionable strategies. The following section translates these insights into theoretical and practical implications, offering guidance for stakeholders seeking to foster sustainable and digitally enabled agricultural supply chains.

5.1 Theoretical implications

The role of digitalization in addressing upcoming agri-food industry challenges was emphasized by policymakers. Still, it remained unclear how digitalization should be used and governed. National governments and various interest groups currently hold contrasting opinions about the best administration tactics. The EU representatives in the conference meeting went into greater detail about the value of digitalization for breaking into new markets and acquiring and preserving market benefits in a global context. To address these unknowns and uncertainties, adaptive and dynamic governance approaches are necessary. These methodologies should promote continuous, incremental learning and adaptation to support cautious handling of complexity, scientific uncertainty, and/or sociopolitical uncertainty.

The farming sector has been recognized as a significant target sector by the EU and other member countries of the OECD to lower CO_2 emissions. Legislators consider digital technology as a key technological instrument for creating "climate-smart agriculture" and for greening agriculture. Agrarian policies, however, have to support social sustainability proactively. It is challenging to provide fair and equitable working conditions because labor is expensive, and farms are under huge pressure from supermarkets and wholesalers to cut costs and increase quality. We need new policy thinking that allows "decent work" in

Downloaded from http://www.emerald.com/jadee/article-pdf/doi/10.1108/JADEE-03-2025-0117/10837281/jadee-03-2025-0117en.pdf by Institut Latihan Statistik Malaysia user on 02 Dec

agriculture as a choice instead of just automating and substituting manual labor in agriculture. Sustainable agriculture businesses have to be tolerant of high labor costs, for example, by adopting an alternative mechanism of European CAP subsidies per worker rather than per hectare, which might benefit more labor-intensive sustainable forms of agricultural production.

The framework that has been developed can be applied by Agri-cooperative managers and partners to determine what level of the Agri-cooperative organization's digitalization process has been reached and continue development. With regards to policy, the Agri-Coop DDT can assist institutions in understanding Agri-cooperatives' I4.0 maturity level and consequently be able to create improved policy for long-term sustainability.

5.2 Practical implications

The findings of this study carry significant practical implications for stakeholders engaged in agricultural supply chains. By identifying the most critical causal barriers, such as lack of management commitment, inadequate prioritization of circular economy practices, shortage of skilled workforce, and insufficient government support, this research provides clear directions for targeted interventions. Managers and cooperative leaders can use the causal insights to prioritize capacity-building and training programs, while policymakers can focus on creating enabling frameworks through financial incentives, infrastructure development, and regulatory clarity. At the same time, private sector actors and technology providers are encouraged to design context-specific digital solutions that directly address these bottlenecks. Collectively, these strategies can help overcome systemic obstacles, accelerate Industry 4.0 adoption, and promote more sustainable and resilient agri-food systems.

Information and communication technologies (ICTs) are increasingly catalyzing agricultural development across Europe, Central Asia, and other regions. The condition of the digital agriculture ecosystem varies across countries and regions, reflecting differences in institutional systems, infrastructure, and policy implementation. The adoption of national digital agriculture strategies—observed in countries such as Albania, Armenia, Turkey, China, and the US has demonstrated mixed results, highlighting the need for coordinated efforts by various stakeholders. Government support, state funding, private investment, and training programs are key enablers for successful e-agriculture adoption, while infrastructure development remains a critical requirement. Digital agriculture can be practically implemented in developing nations and the Global South by building inclusive digital public infrastructure, investing in rural connectivity and training, and fostering multi-stakeholder collaborations. Governments can develop clear digital agriculture roadmaps, as done in India, Ethiopia, and Kenya, that prioritize context-specific solutions like interactive advisory systems, AI-powered mobile extension platforms, and affordable precision tools tailored for smallholders. Key steps involve expanding mobile and internet coverage in rural areas, subsidizing technology adoption for underserved farmers, and leveraging partnerships between government, private sector, research institutions, and farmer organizations to ensure solutions match local needs and skills. Successful case studies show that such approaches can lead to measurable increases in productivity, farm income, and resilience, empowering millions of rural households to overcome traditional barriers and fully participate in modern, climate-smart value chains (Porciello *et al.*, 2022; Kitole, 2024).

To translate these observations into actionable strategies, practical implications can be categorized by stakeholder type as per Table 9. Recent practices demonstrate the effectiveness of these approaches. For example, Germany's horticulture and arable farming industries use digital technologies to intensify labor processes, while Canadian greenhouse operations employ automated harvesting machines and wearable devices to monitor worker performance. Regulatory initiatives in India, such as Make in India, Skills India, and Start-Up India, further support innovation by promoting:

Downloaded from http://www.emerald.com/jadee/article-pdf/doi/10.1108/JADEE-03-2025-0117/10837281/jadee-03-2025-0117en.pdf by Institut Latihan Statistik Malaysia user on 02 Dec

Table 9. Framework of practical implications for stakeholders in digital agriculture

Stakeholder	Key actions/Recommendations	Rationale/Expected outcome	Priority
Government	Develop national digital agriculture strategies; provide financial incentives; enhance digital infrastructure; implement supportive regulations and standards	Creates an enabling environment; facilitates large-scale adoption; ensures sustainability and governance compliance	High
Cooperatives/ Farmer Groups	Organize training programs and workshops; facilitate knowledge sharing; act as intermediaries with technology providers	Increases adoption rates; strengthens community capacity; reduces implementation barriers	Medium
Farmers/ Practitioners	Adopt precision agriculture tools, automated animal husbandry systems (AMS, AFS), and smart monitoring devices; participate in training and upskilling programs	Directly improves productivity, efficiency, and sustainability at the farm level	High
Private Sector/ Technology Providers	Provide customized ICT solutions; support farmer training; invest in R&D for sustainable technologies	Ensures technology relevance; accelerates innovation diffusion; reduces skill gaps	Medium
Educational/ Research Institutions	Develop curricula for digital agriculture; conduct pilot studies and demonstrations; collaborate with government and industry	Builds long-term workforce capacity; promotes evidence-based adoption and innovation	Medium

(1) Clear vision and strategic objectives

(2) Establishing global linkages

(3) Enhancing industrial competitiveness

(4) Ensuring sustainability

(5) Enabling an innovation-friendly ecosystem for technology adaptation

By prioritizing actions across stakeholder groups, these practical implications can guide policymakers, cooperatives, farmers, and private partners in accelerating digital agriculture adoption while ensuring sustainability and efficiency.

For policymakers in developing economies, the findings underscore the urgent need to create enabling environments that support digital and sustainable transitions in agriculture. Targeted policies such as subsidies for precision technologies, tax incentives for green practices, and regulatory clarity on data governance can lower adoption barriers and encourage broader participation. Beyond policy, societal benefits include enhanced food security, reduced post-harvest losses, and improved livelihoods for smallholder farmers who form the backbone of agri-food systems. Strengthening digital literacy and fostering inclusive access to technologies are critical to avoid widening inequalities, ensuring that digital transformation in agriculture contributes not only to economic growth but also to equitable and sustainable rural development.

6. Conclusion, limitations, and future scope

Industry 4.0 has the potential to integrate circular economy practices within Agri Supply Chains (ASCs) by introducing new value propositions, enhancing information transparency, and enabling monitoring of environmental externalities. This study represents one of the pioneering efforts to explicitly identify and analyze barriers to Industry 4.0 adoption for sustainability in ASCs from a circular economy perspective. Using DEMATEL methodology,

Downloaded from http://www.emerald.com/jadee/article-pdf/doi/10.1108/JADEE-03-2025-0117/10837281/jadee-03-2025-0117en.pdf by Institut Latihan Statistik Malaysia user on 02 Dec

the causal relationships among barriers were modeled, revealing critical influences on adoption processes. The findings highlighted that "Lack of management commitment," "Lack of prioritizing circular economy practices," "Lack of skilled workers," and "Lack of government support" constitute the most significant causal barriers hindering Industry 4.0 implementation. These barriers serve as root causes that, when addressed effectively, can alleviate subsequent obstacles and accelerate sustainable technology adoption. This insight is vital for practitioners and policymakers aiming to create a conducive ecosystem that supports digital transformation within the agri-food sector, particularly in developing economies where sustainability challenges are most acute.

However, this study is not without limitations. The relatively small expert sample, while comprising highly experienced managers, may restrict the generalizability of the findings. In addition, the reliance on judgment-based methods such as Fuzzy Delphi and DEMATEL, though appropriate for exploratory studies, introduces subjectivity into the results. Finally, the absence of empirical validation in real supply chains limits the ability to fully capture dynamic and operational complexities. The study's emphasis on a causal barrier structure provides actionable knowledge to prioritize interventions strategically. For example, fostering management buy-in and government backing should be at the forefront of policy and organizational efforts to enable workforce skill development and circular economy alignment. Moreover, Industry 4.0 technologies are positioned as indispensable tools for delivering safe, nutritious, and environmentally sustainable food systems in developing countries.

While this research offers a solid foundational framework, future work can enhance its external validity through multi-case analyses, comparative cross-country studies, and the adoption of action research methodologies. These directions can further uncover emerging enablers and barriers while tailoring mitigation strategies across contexts. Future research should therefore focus on validating these findings through large-scale empirical studies and longitudinal data from real agricultural supply chains. Integrating hybrid approaches such as combining quantitative surveys, simulation models, or case-based evidence with judgment-based methods could improve robustness. Comparative studies across regions and stakeholder groups would also enrich understanding of contextual variations and enable the development of more tailored strategies for Industry 4.0 adoption.

References

Aamer, A.M., Al-Awlaqi, M.A., Affia, I., Arumsari, S. and Mandahawi, N. (2021), "The internet of things in the food supply chain: adoption challenges", *Benchmarking: An International Journal*, Vol. 28 No. 8, pp. 2521-2541, doi: 10.1108/BIJ-07-2020-0371.

Ajer, B., Ngare, L. and Macharia, I. (2024), "Drivers of innovation in the agro-food micro, small and medium enterprises of Uganda", *Journal of Agribusiness in Developing and Emerging Economies*, Vol. 14 No. 5, pp. 979-996, doi: 10.1108/jadee-09-2022-0206.

Akbari, M., Kok, S.K., Hopkins, J., Frederico, G.F., Nguyen, H. and Alonso, A.D. (2023), "The changing landscape of digital transformation in supply chains: impacts of industry 4.0 in Vietnam", *International Journal of Logistics Management*, Vol. 35 No. 4, pp. 1040-1072, doi: 10.1108/IJLM-11-2022-0442.

Akzar, R., Peralta, A. and Umberger, W. (2025), "Adoption of dairy feed technology bundles improves smallholder dairy farmers' milk production", *Journal of Agribusiness in Developing and Emerging Economies*, Vol. 15 No. 2, pp. 269-287, doi: 10.1108/jadee-12-2022-0267.

Ali, I. and Phan, H.M. (2022), "Industry 4.0 technologies and sustainable warehousing: a systematic literature review and future research agenda", *International Journal of Logistics Management*, Vol. 33 No. 2, pp. 644-662, doi: 10.1108/IJLM-05-2021-0277.

Amjad, M.S., Rafique, M.Z. and Khan, M.A. (2021), "Leveraging optimized and cleaner production through industry 4.0", *Sustainable Production and Consumption*, Vol. 26, pp. 859-871, doi: 10.1016/j.spc.2021.01.001.

Downloaded from http://www.emerald.com/jadee/article-pdf/doi/10.1108/JADEE-03-2025-0117/10837281/jadee-03-2025-0117en.pdf by Institut Latihan Statistik Malaysia user on 02 Dec

Bernhardt, H., Bozkurt, M., Brunsch, R., Colangelo, E., Herrmann, A., Horstmann, J., Kraft, M., Marquering, J., Steckel, T., Tapken, H., Weltzien, C. and Westerkamp, C. (2021), "Challenges for agriculture through industry 4.0", *Agronomy*, Vol. 11 No. 10, pp. 1-10, doi: 10.3390/agronomy11101935.

Cagliano, R. and Canterino, F. (2022), "It takes two to tango : analyzing the relationship between technological and administrative process innovations in industry 4 . 0", *Technological Forecasting and Social Change*, Vol. 180, 121675, doi: 10.1016/j.techfore.2022.121675.

Chavhan, R. and Dutta, P. (2025), "Redesigning quick commerce fresh and short food supply chains: circular economy strategies for sustainable last-mile operations", *British Food Journal*, Vol. 127 No. 5, pp. 1676-1701, doi: 10.1108/BFJ-05-2024-0560.

Ciruela-Lorenzo, A.M., Del-Aguila-Obra, A.R., Padilla-Meléndez, A. and Plaza-Angulo, J.J. (2020), "Digitalization of agri-cooperatives in the smart agriculture context. Proposal of a digital diagnosis tool", *Sustainability (Switzerland)*, Vol. 12 No. 4, p. 1325, doi: 10.3390/su12041325.

Fang, D. and Zhang, X. (2021), "The protective effect of digital financial inclusion on agricultural supply chain during the covid-19 pandemic: evidence from China", *Journal of Theoretical and Applied Electronic Commerce Research*, Vol. 16 No. 7, pp. 3202-3217, doi: 10.3390/JTAER16070174.

Gadekar, R., Sarkar, B. and Gadekar, A. (2022), "Investigating the relationship among Industry 4.0 drivers, adoption, risks reduction, and sustainable organizational performance in manufacturing industries: an empirical study", *Sustainable Production and Consumption*, Vol. 31, pp. 670-692, doi: 10.1016/j.spc.2022.03.010.

Garay-Rondero, C.L., Martinez-Flores, J.L., Smith, N.R., Caballero Morales, S.O. and Aldrette-Malacara, A. (2020), "Digital supply chain model in Industry 4.0", *Journal of Manufacturing Technology Management*, Vol. 31 No. 5, pp. 887-933, doi: 10.1108/JMTM-08-2018-0280.

Gardas, B.B., Raut, R.D., Cheikhrouhou, N. and Narkhede, B.E. (2019), "A hybrid decision support system for analyzing challenges of the agricultural supply chain", *Sustainable Production and Consumption*, Vol. 18, pp. 19-32, doi: 10.1016/j.spc.2018.11.007.

Garske, B., Bau, A. and Ekardt, F. (2021), "Digitalization and ai in European agriculture: a strategy for achieving climate and biodiversity targets?", *Sustainability (Switzerland)*, Vol. 13 No. 9, pp. 1-21, doi: 10.3390/su13094652.

Ghaemi Rad, T., Sadeghi-Niaraki, A., Abbasi, A. and Choi, S.M. (2018), "A methodological framework for assessment of ubiquitous cities using ANP and DEMATEL methods", *Sustainable Cities and Society*, Vol. 37, November 2017, pp. 608-618, doi: 10.1016/j.scs.2017.11.024.

Goller, M., Caruso, C. and Harteis, C. (2021), "Digitalisation in agriculture: knowledge and learning requirements of German dairy farmers", *International Journal for Research in Vocational Education and Training*, Vol. 8 No. 2, pp. 208-223, doi: 10.13152/IJRVET.8.2.4.

Gwo-Hshiung, T., Tzeng, G.H. and Huang, J.J. (2011), *Multiple Attribute Decision Making: Methods and Applications*, CRC Press.

Haggag, W.M. (2021), "Agricultural digitalization and rural development in COVID-19 response plans: a review article", *International Journal of Agricultural Technology*, Vol. 17 No. 1, pp. 67-74.

Haider, M., Jha, A.K., Raut, R., Kumar, M. and Ghoshal, S. (2024), "Redesigning short and perishable food supply chains getting insight from the causal analysis of challenges to sustainable development", *British Food Journal*, Vol. 127 No. 5, pp. 1620-1647, doi: 10.1108/BFJ-04-2024-0362.

ILO (2019), "World employment social outlook-trend 2019", International Labour Organization, Geneva, available at: https://www.ilo.org/sites/default/files/wcmsp5/groups/public/@dgreports/@dcomm/@publ/documents/publication/wcms_670542.pdf

Ingram, J. and Maye, D. (2020), "What are the implications of digitalisation for agricultural knowledge?", *Frontiers in Sustainable Food Systems*, Vol. 4, pp. 1-6, doi: 10.3389/fsufs.2020.00066.

Downloaded from http://www.emerald.com/jadee/article-pdf/doi/10.1108/JADEE-03-2025-0117/10837281/jadee-03-2025-0117en.pdf by Institut Latihan Statistik Malaysia user on 02 Dec

Ishikawa, A., Amagasa, M., Shiga, T., Tomizawa, G., Tatsuta, R. and Mieno, H. (1993), "The max-min Delphi method and fuzzy Delphi method via fuzzy integration", *Fuzzy Sets and Systems*, Vol. 55 No. 3, pp. 241-253, doi: 10.1016/0165-0114(93)90251-C.

Jain, M., Soni, G., Mangla, S.K., Verma, D., Toshniwal, V.P. and Ramtiyal, B. (2025), "Mediating and moderating role of socioeconomic and technological factors in assessing farmer's attitude towards adoption of Industry 4.0 technology", *British Food Journal*, Vol. 127 No. 5, pp. 1810-1830, doi: 10.1108/BFJ-12-2023-1139.

Jayashree, S., Reza, M.N.H., Malarvizhi, C.A.N., Gunasekaran, A. and Rauf, M.A. (2022), "Testing an adoption model for Industry 4.0 and sustainability: a Malaysian scenario", *Sustainable Production and Consumption*, Vol. 31, pp. 313-330, doi: 10.1016/j.spc.2022.02.015.

Kaleli, S.S. (2025), "Introduction of industry 5.0", in Grima, S., Kaleli, S.S., Baygin, M. and Boztepe, E. (Eds), *Business Challenges and Opportunities in the Era of Industry 5.0 (Emerald Studies in Finance, Insurance, and Risk Management)*, Emerald Publishing, Leeds, pp. 1-18, doi: 10.1108/978-1-83549-676-320251001.

Kamble, S.S. and Gunasekaran, A. (2020), "Big data-driven supply chain performance measurement system: a review and framework for implementation", *International Journal of Production Research*, Vol. 58 No. 1, pp. 65-86, doi: 10.1080/00207543.2019.1630770.

Kitole, N., Liu, Y., Wang, J., Noguchi, N. and He, Y. (2024), "Mobile platforms fostering advisory support for smallholders in sub-Saharan Africa", *Computers and Electronics in Agriculture*, Vol. 204, 107546, doi: 10.1016/j.compag.2024.107546.

Kumar, R., Singh, R.K. and Dwivedi, Y.K. (2020a), "Application of industry 4.0 technologies in SMEs for ethical and sustainable operations: analysis of challenges", *Journal of Cleaner Production*, Vol. 275, 124063, doi: 10.1016/j.jclepro.2020.124063.

Kumar, A., Mangla, S.K., Kumar, P. and Karamperidis, S. (2020b), "Challenges in perishable food supply chains for sustainability management: a developing economy perspective", *Bus. Strateg. Environ.*, Vol. 29 No. 5, pp. 1809-1831, doi: 10.1002/bse.2470.

Kumar, S., Raut, R.D., Nayal, K., Kraus, S., Yadav, V.S. and Narkhede, B.E. (2021), "To identify industry 4.0 and circular economy adoption barriers in the agriculture supply chain by using ISM-ANP", *Journal of Cleaner Production*, Vol. 293, 126023, doi: 10.1016/j.jclepro.2021.126023.

Kumari, S., Singh, R.K. and Gunasekaran, A. (2023), "Antecedents of agriculture supply chain performance during COVID-19: an emerging economy perspective", *Environment, Development and Sustainability*, Vol. 25 No. 9, pp. 8775-8798, doi: 10.1007/s10668-022-02718-2.

Lagarda-Leyva, E.A., Morales-Mendoza, L.F., Ríos-Vázquez, N.J., Ayala-Espinoza, A. and Nieblas-Armenta, C.K. (2019), "Managing plastic waste from agriculture through reverse logistics and dynamic modeling", *Clean Technologies and Environmental Policy*, Vol. 21 No. 7, pp. 1415-1432, doi: 10.1007/s10098-019-01700-5.

Latino, M.E., Corallo, A., Menegoli, M. and Nuzzo, B. (2021), "Agriculture 4.0 as enabler of sustainable agri-food: a proposed taxonomy", *IEEE Transactions on Engineering Management*, Vol. 70 No. 10, pp. 1-19, doi: 10.1109/TEM.2021.3101548.

Latino, M.E., Menegoli, M. and Corallo, A. (2022), "Agriculture digitalization: a global examination based on bibliometric analysis", *IEEE Transactions on Engineering Management*, Vol. 71, pp. 1-16, doi: 10.1109/TEM.2022.3154841.

Liang, Y., Wang, H. and Zhao, X. (2022), "Analysis of factors affecting economic operation of electric vehicle charging station based on DEMATEL-ISM", *Computers and Industrial Engineering*, Vol. 163, 107818, doi: 10.1016/j.cie.2021.107818.

Lin, W., Huang, X., Fang, H., Wang, V., Hua, Y., Wang, J., Yin, H., Yi, D. and Yau, L. (2020), "Blockchain technology in current agricultural systems: from techniques to applications", *IEEE Access*, Vol. 8, pp. 143920-143937, doi: 10.1109/ACCESS.2020.3014522.

Lioutas, E.D., Charatsari, C. and De Rosa, M. (2021), "Digitalization of agriculture: a way to solve the food problem or a trolley dilemma?", *Technology in Society*, Vol. 67, 101744, doi: 10.1016/j.techsoc.2021.101744.

Downloaded from http://www.emerald.com/jadee/article-pdf/doi/10.1108/JADEE-03-2025-0117/10837281/jadee-03-2025-0117en.pdf by Institut Latihan Statistik Malaysia user on 02 Dec

Liu, Y., Ma, X., Shu, L., Hancke, G.P. and Abu-Mahfouz, A.M. (2021), "From industry 4.0 to agriculture 4.0: current status, enabling technologies, and research challenges", *IEEE Trans. Ind. Informatics*, Vol. 17 No. 6, pp. 4322-4334, doi: 10.1109/TII.2020.3003910.

Lovkova, E.S., Kashitsina, T.N., Sultanova, A.V. and Simonov, S.Y. (2022), "Digitalization in agriculture", *IOP Conference Series: Earth and Environmental Science*, Vol. 988 No. 3, p. 032015, doi: 10.1088/1755-1315/988/3/032015.

Malekzadeh, G., Kazemi, M., Lagzian, M. and Mortazavi, S. (2016), "Modeling organizational intelligence using DEMATEL method in Iranian public universities", *Journal of Modelling in Management*, Vol. 11 No. 1, pp. 134-153, doi: 10.1108/JM2-12-2013-0062.

Martens, K. and Zscheischler, J. (2022), "The digital transformation of the agricultural value chain: discourses on opportunities, challenges and controversial perspectives on governance approaches", *Sustainability (Switzerland)*, Vol. 14 No. 7, p. 3905, doi: 10.3390/su14073905.

Mastos, T.D., Nizamis, A., Vafeiadis, T., Alexopoulos, N., Ntinas, C., Gkortzis, D., Papadopoulos, A., Ioannidis, D. and Tzovaras, D. (2020), "Industry 4.0 sustainable supply chains: an application of an IoT enabled scrap metal management solution", *Journal of Cleaner Production*, Vol. 269, 122377, doi: 10.1016/j.jclepro.2020.122377.

Mehmood, A., Ahmed, S., Viza, E., Bogush, A. and Ayyub, R.M. (2021), "Drivers and barriers towards circular economy in agri-food supply chain: a review", *Business Strategy and Development*, Vol. 4 No. 4, pp. 465-481, doi: 10.1002/bsd2.171.

Mendes, J.A.J., Carvalho, N.G.P., Mourarias, M.N., Careta, C.B., Zuin, V.G. and Gerolamo, M.C. (2022), "Dimensions of digital transformation in the context of modern agriculture", *Sustainable Production and Consumption*, Vol. 34, pp. 613-637, doi: 10.1016/j.spc.2022.09.027.

Mishra, D. and Satapathy, S. (2021), "Technology adoption to reduce the harvesting losses and wastes in agriculture", *Clean Technologies and Environmental Policy*, Vol. 23 No. 7, pp. 1947-1963, doi: 10.1007/s10098-021-02075-2.

Mogale, D.G., Ghadge, A., Cheikhrouhou, N. and Tiwari, M.K. (2023), "Designing a food supply chain for enhanced social sustainability in developing countries", *International Journal of Production Research*, Vol. 61 No. 10, pp. 3184-3204, doi: 10.1080/00207543.2022.2078746.

Mohapatra, S., Sainath, B., Kc, A., Lal, H., K, N.R., Bhandari, G. and Nyika, J. (2025), "Application of blockchain technology in the agri-food system: a systematic bibliometric visualization analysis and policy imperatives", *Journal of Agribusiness in Developing and Emerging Economies*, Vol. 15 No. 2, pp. 288-310, doi: 10.1108/jadee-10-2022-0237.

Muduli, K.K., Luthra, S., Kumar Mangla, S., Jabbour, C.J.C., Aich, S. and de Guimarães, J.C.F. (2020), "Environmental management and the "soft side" of organisations: discovering the most relevant behavioural factors in green supply chains", *Business Strategy and the Environment*, Vol. 29 No. 4, pp. 1647-1665, doi: 10.1002/bse.2459.

Nayal, K., Raut, R.D. and Narkhede, B.E. (2023), "Are artificial intelligence and machine learning suitable to tackle the COVID-19 impacts? An agriculture supply chain perspective", *Benchmarking: An International Journal*, Vol. 30 No. 2, pp. 382-406.

Patidar, R. and Agrawal, S. (2020), "Restructuring the Indian agro-fresh food supply chain network: a mathematical model formulation", *Clean Technologies and Environmental Policy*, Vol. 22 No. 10, pp. 2053-2077, doi: 10.1007/s10098-020-01955-3.

Porciello, J., Coggins, S., Mabaya, E. and Otunba-Payne, G. (2022), "Digital agriculture services in low-and middle-income countries: a systematic scoping review", *Global Food Security*, Vol. 34, 100640, doi: 10.1016/j.gfs.2022.100640.

Prause, L. (2021), "Digital agriculture and labor: a few challenges for social sustainability", *Sustainability (Switzerland)*, Vol. 13 No. 11, p. 5980, doi: 10.3390/su13115980.

Qin, T., Wang, L., Zhou, Y., Guo, L., Jiang, G. and Zhang, L. (2022), "Digital technology-and-services-driven sustainable transformation of agriculture: cases of China and the EU", *Agriculture*, Vol. 12 No. 2, pp. 1-16, doi: 10.3390/agriculture12020297.

Downloaded from http://www.emerald.com/jadee/article-pdf/doi/10.1108/JADEE-03-2025-0117/10837281/jadee-03-2025-0117en.pdf by Institut Latihan Statistik Malaysia user on 02 Dec

Rajendran, P., Kumar, R. and Subramanian, K. (2025), "Enerchainability in agriculture supply chains: examining the adoption of blockchain and its energy efficiency from farmers' perspective", *International Journal of Energy Economics and Policy*, Vol. 15 No. 1, pp. 101-115.

Rolandi, S., Brunori, G., Bacco, M. and Scotti, I. (2021), "The digitalization of agriculture and rural areas: towards a taxonomy of the impacts", *Sustainability (Switzerland)*, Vol. 13 No. 9, pp. 1-16, doi: 10.3390/su13095172.

Sarkar, B.D., Sharma, I. and Shardeo, V. (2025), "A multi-method examination of barriers to traceability in Industry 5.0-enabled digital food supply chains", *International Journal of Logistics Management*, Vol. 36 No. 2, pp. 354-380, doi: 10.1108/IJLM-01-2024-0010.

Schöggl, J.P., Rusch, M., Stumpf, L. and Baumgartner, R.J. (2023), "Implementation of digital technologies for a circular economy and sustainability management in the manufacturing sector", *Sustainable Production and Consumption*, Vol. 35, pp. 401-420, doi: 10.1016/j.spc.2022.11.012.

Sharma, R., Kamble, S., Mani, V. and Belhadi, A. (2022), "An empirical investigation of the influence of industry 4.0 technology capabilities on agriculture supply chain integration and sustainable performance", *IEEE Transactions on Engineering Management*, Vol. 71, pp. 12364-12384, doi: 10.1109/tem.2022.3192537.

Sharma, R., Shishodia, A., Kamble, S., Gunasekaran, A. and Belhadi, A. (2024), "Agriculture supply chain risks and COVID-19: mitigation strategies and implications for the practitioners", *International Journal of Logistics Research and Applications*, Vol. 27 No. 11, pp. 2351-2377, doi: 10.1080/13675567.2020.1830049.

Shen, Z., Wang, S., Boussemart, J.P. and Hao, Y. (2022), "Digital transition and green growth in Chinese agriculture", *Technological Forecasting and Social Change*, Vol. 181, 121742, doi: 10.1016/j.techfore.2022.121742.

Sonar, H., Sharma, I., Ghag, N. and Raje, B. (2024a), "Harvesting sustainability: assessing Industry 4.0 in agri-food supply chains", *International Journal of Logistics Management*, Vol. 36 No. 2, pp. 647-668, doi: 10.1108/IJLM-10-2023-0443.

Sonar, H., Sharma, I., Ghag, N. and Singh, R.K. (2024b), "Barriers for achieving sustainable agri supply chain: study in context to Indian MSMEs", *International Journal of Logistics Research and Applications*, pp. 1-20, doi: 10.1080/13675567.2024.2345359.

Toktaş-Palut, P. (2022), "Analyzing the effects of Industry 4.0 technologies and coordination on the sustainability of supply chains", *Sustainable Production and Consumption*, Vol. 30, pp. 341-358, doi: 10.1016/j.spc.2021.12.005.

Tseng, M.L., Chiu, A.S.F., Chien, C.F. and Tan, R.R. (2019), "Pathways and barriers to circularity in food systems", *Resources, Conservation and Recycling*, Vol. 143, January, pp. 236-237, doi: 10.1016/j.resconrec.2019.01.015.

Uygun, Ö., Kaçamak, H. and Kahraman, Ü.A. (2014), "An integrated DEMATEL and Fuzzy ANP techniques for evaluation and selection of outsourcing provider for a telecommunication company", *Computers and Industrial Engineering*, Vol. 86, pp. 137-146, doi: 10.1016/j.cie.2014.09.014.

Verdouw, C.N., Robbemond, R.M., Verwaart, T., Wolfert, J. and Beulens, A.J.M. (2018), "A reference architecture for IoT-based logistic information systems in agri-food supply chains", *Enterprise Information Systems*, Vol. 12 No. 7, pp. 755-779, doi: 10.1080/17517575.2015.1072643.

Verza, M., Camanzi, L., Rota, C., Mulazzani, L., Malorgio, G. and Mattas, K. (2025), "From farm to shelf: managing agrobiodiversity and product diversity in agri-food supply chains", *British Food Journal*, Vol. 127 No. 13, pp. 322-337, doi: 10.1108/BFJ-11-2024-1168.

Yadav, V.S., Kumar, S. and Prashar, A. (2024), "Development of a framework for blockchain technology-based net zero strategies in the agri-food supply chain", *Business Strategy and the Environment*, Vol. 33 No. 2, pp. 709-723.

Zhang, J. (2017), "Evaluating regional low-carbon tourism strategies using the fuzzy Delphi- analytic network process approach", *Journal of Cleaner Production*, Vol. 141, pp. 409-419, doi: 10.1016/j.jclepro.2016.09.122.

Downloaded from http://www.emerald.com/jadee/article-pdf/doi/10.1108/JADEE-03-2025-0117/10837281/jadee-03-2025-0117en.pdf by Institut Latihan Statistik Malaysia user on 02 Dec

Zhao, G., Ye, C., Dennehy, D., Liu, S., Harfouche, A. and Olan, F. (2024), "Analysis of barriers to adopting Industry 4.0 to achieve agri-food supply chain sustainability: a group-based fuzzy analytic hierarchy process", *Business Strategy and the Environment*, Vol. 33 No. 8, pp. 8559-8586, doi: 10.1002/bse.3928.

Zkik, K., Belhadi, A., Rehman Khan, S.A., Kamble, S.S., Oudani, M. and Touriki, F.E. (2023), "Exploration of barriers and enablers of blockchain adoption for sustainable performance: implications for e-enabled agriculture supply chains", *International Journal of Logistics Research and Applications*, Vol. 26 No. 11, pp. 1498-1535, doi: 10.1080/13675567.2022.2088707.

Journal of Agribusiness in Developing and Emerging Economies

Corresponding author
Shashank Kumar can be contacted at: shashank.k@iimbg.ac.in

For instructions on how to order reprints of this article, please visit our website:
www.emeraldgrouppublishing.com/licensing/reprints.htm
Or contact us for further details: **permissions@emeraldinsight.com**

Downloaded from http://www.emerald.com/jadee/article-pdf/doi/10.1108/JADEE-03-2025-0117/10837281/jadee-03-2025-0117en.pdf by Institut Latihan Statistik Malaysia user on 02 Dec