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Understanding digital capabilities and their impacts on Australian agri-food supply chain resilience: Engineering vs. socio-ecological thinking

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ABSTRACT

Many agri-food supply chains (SCs) are vulnerable to sudden disruptions (i.e., shocks), which can have devastating impacts. SC member firms' digital capabilities (as routinized and integrated resource bundles) have the potential to address these challenges, yet their nature and differentiated impacts on engineering versus socio-ecological resilience are not well understood in the present literature. The purpose of this study is to address these gaps. First, a comprehensive taxonomy of five digital capabilities (labelled LogisticsTech, SecureData, ClientValue, InsightDecision, and InnovateTech) is developed, along with a set of nine resilience criteria/sub-criteria useful for resiliency evaluation. This was achieved through using a narrative literature review, a content analysis, validated by a Delphi study, and semi-structured interviews. Second, the relative impacts of these capabilities on resilience are assessed through pairwise comparison, network analysis, and system dynamics modelling across six Australian agri-food SCs (Grains, Red Meat, Dairy, Horticulture, Seafood, and Wine). The study findings reveal that Australian agri-food SC members' digital capabilities play distinct but interconnected roles in enhancing resilience, with their impact varying across persistence (engineering), adaptation, and transformation (socio-ecological) over different time frames. LogisticsTech is crucial for short-term, while SecureData safeguards long-term persistence. Moreover, InsightDecision supports immediate adaptation, ClientValue facilitates long-term adaptation, and InnovateTech drives systemic transformation and future-ready SCs. The study offers strategic insights for managers and policymakers to align digital technology adoption with resilience objectives.

1. Introduction

Agri-food supply chains (SCs) play a crucial role in Australia's economy, contributing significantly to both food security and financial stability. Australian agri-food SCs include every stage, from agricultural production and processing to distribution and retail. Due to Australia's unique geography and diverse environments, agri-food SCs often require sophisticated transportation and storage systems to maintain product quality over long durations and distances. However, their extensive and distributed nature makes them highly susceptible to sudden disruptions, often referred to as "shocks." These shocks can arise from various sources, including economic fluctuations, geopolitical tensions, international crises, trade disputes, health emergencies, and rapid technological developments (Barbosa, 2021; Jayaram et al., 2014; Kumar et al., 2021). Moreover, increasingly (Taghikhah et al., 2019) frequent and severe climate-related events, such as droughts, bushfires, and floods, further exacerbate risks. Given this heightened vulnerability, studying the resilience of Australian agri-food SCs is critical to maintaining their stability and efficiency in the face of shocks (Rahman et al., 2023, 2024).

The extant SC resilience literature tends to invoke an "engineering" lens when examining SC resilience to shocks, whereby an SC is resilient if it returns to its original state post-shock (this study uses the label "persistence" to reflect this notion of SC resilience) (McCarthy et al., 2017). Few studies consider the emergent "social-ecological" resilience framework, which considers resilience as "adaptation" (i.e., a short-term SC reconfiguration that accommodates new circumstances) and "transformation" (i.e., a more fundamental, long-term SC reconfiguration that accommodates new circumstances) (Wieland et al.,

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2023; Wieland and Durach, 2021; Herburger et al., 2024). Evidence shows that individual digital technologies help support SC persistence (Faruquee et al., 2021; Yang et al., 2021). Internet of Things (IoT), big data analytics, and cloud computing are among the most common technologies shown in the literature as having positive effects on SC visibility, traceability, and stability, all of which are important aspects of SC persistence (Abbas and Marwat, 2020; Lin et al., 2019; Engelseth et al., 2019). Few studies, however, examine the effects of digital technologies on SC adaptation and SC transformation, which are central to the social–ecological perspective of SC resilience (Wieland et al., 2023; Wieland and Durach, 2021; Herburger et al., 2024).

Moreover, current SC resilience studies treat digital technologies on an individual basis, which does not reflect the reality that digital technologies are normally embedded in a broader combination of resources, which the firm utilizes through routines, processes and systems (Ghobakhloo et al., 2025; Tortorella et al., 2022). Hence, there is also a need to understand the combined effects of digital technologies as digital capabilities on Australian agri-food SC resilience (Lezoche et al., 2020; Çolak et al., 2024). In taking this step, a more managerially relevant interpretation of the effects of digital technologies (as parts of broader digital capabilities) is possible.

This study addresses two research questions (RQs): The first research question is: *what are the digital capabilities that affect Australian agri-food SC resilience? (RQ1)*

To address RQ1, the study draws on a Narrative Literature Review (Green et al., 2006) and Content Analysis (Burnard, 1995), validated through a Delphi study (Okoli and Pawlowski, 2004), and Semi-Structured Interviews (Mason, 2002). These methods are used to identify and describe a taxonomy of five digital capabilities — LogisticsTech, SecureData, ClientValue, InsightDecision, and InnovateTech — along with a set of criteria useful for measuring SC persistence, SC adaptation, and SC transformation. This approach captures notions of both engineering and social–ecological perspectives of SC resilience (Wieland et al., 2023; Wieland and Durach, 2021; Herburger et al., 2024). Hence, this study contributes a new digital capabilities taxonomy to the SC resilience literature to reconcile the disparate treatment of digital technologies currently evident (Lezoche et al., 2020; Çolak et al., 2024). This innovation is also more consistent with current managerial practice, where SC member firms are more likely to use a combination of digital technologies, and other resources, through structured routines, processes and systems, to manage SC shocks (Lezoche et al., 2020; Çolak et al., 2024). This also highlights the importance of digital capabilities as the basis for analysis in SC resilience research rather than specific digital technologies in isolation. The study also develops a set of nine resilience criteria/sub-criteria useful for their evaluation, which should also aid in the measurement and analysis of SC digital capabilities.

The second research question is: *what are the effects of digital capabilities on Australian agri-food SC resilience, considering both the engineering (persistence) and social–ecological (adaptation and transformation) perspectives? (RQ2)*

To address RQ2, the study adopts a multi-method approach, recognizing that SC resilience is a multidimensional concept encompassing persistence, adaptation, and transformation. Given their complexities, these dimensions must be understood in relation to time, considering both their immediate effects and their evolving influence over the long term. The Pairwise Comparison method (Kuo and Chen, 2023; Saaty, 1990) evaluates the relative contributions of digital capabilities to SC resilience by deriving weights that reflect their importance across resilience criteria. These weights serve as the foundation for subsequent analyses. Network Analysis (West et al., 2001) builds on these weights to rank digital capabilities for short-term resilience by examining the structural relationships and interdependencies among capabilities and criteria. Furthermore, the study employs System Dynamics modelling (Forrester, 1995) to simulate feedback loops and cumulative impacts, evaluating the interactions between digital capabilities and resilience criteria to determine long-term priorities. Through these steps, the study contributes a fine-grained assessment of the relative effects of digital capabilities on Australian agri-food SC resilience, and one which accounts for both engineering and social–ecological approaches to resilience (Wieland et al., 2023; Wieland and Durach, 2021; Herburger et al., 2024).

The findings reveal significant variations in digital capability impacts for short- and long-term resilience across six Australian agri-food SCs: Grains, Red Meat, Dairy, Horticulture, Seafood, and Wine. From an engineering perspective, LogisticsTech is critical in the short term, while SecureData plays a dominant role in ensuring long-term SC persistence. From a socio-ecological perspective, InsightDecision, ClientValue, and InnovateTech emerge as pivotal for short-term and long-term adaptation and transformation of SC. The paper offers managerial implications to guide the strategic adoption of digital capabilities, highlighting their role in ensuring immediate robustness and enabling future-ready SC systems.

2. Background

2.1. Digital technologies and their impacts on agri-food SC resilience

Previous studies highlight approaches to improve agri-food SC resilience. This includes diversifying suppliers and markets (Leat and Revoredo-Giha, 2013; Taghikhah et al., 2021), implementing risk management practices (Tendall et al., 2015), and developing collaborative relationships between SC actors (Ponomarov and Holcomb, 2009; Latino et al., 2024). More recently, the integration of digital technologies has emerged as a key SC resilience enabler (Lezoche et al., 2020). The importance of Industry 4.0 technologies, such as IoT, artificial intelligence (AI), and Blockchain, continues grow in SCs. Implementing digital technologies in isolation does not inherently lead to higher SC resilience, however (Guan, 2021).

The true value of digital technologies lies in their integration and combination as digital capabilities, defined as the synergistic and effective combination of digital technologies with SC processes (Zhao et al., 2023). Digital capabilities involve the coordinated utilization of various digital tools to achieve strategic objectives and to create value. For instance, a digital capability might require the use of big data analytics for demand forecasting, coupled with cloud computing for data storage and real-time analysis to interpret and act upon the generated insights. Similarly, IoT sensors and big data analytics can anticipate equipment failures and optimize machinery performance (Ahmed et al., 2018). Furthermore, SC management systems that embed AI with cyber–physical systems, such as digital twin technology, can model various disruption scenarios to optimize network design (Maheshwari et al., 2023). While existing studies highlight the importance of digital technologies as vehicles to achieve related outcomes, they do not currently define digital capabilities per se. The comprehensive role of digital technologies in fostering resilience outcomes, therefore, is currently an area in need of further exploration.

Table 1 presents an overview of studies that explore the use of more than one digital technology in agri-food SCs. Several noteworthy trends and gaps in the existing literature are apparent. Firstly, most studies examine a limited combination of technologies, with the most common focus being the integration of IoT with either big data analytics or blockchain technology. While these studies underscore the importance of these technologies, they overlook the broad range of Industry 4.0 technologies now available. This limited scope does not account for the concurrent use of a wider array of technologies by SC actors. Exploring a broader perspective could help shed new light in terms of the interrelationships between Industry 4.0 technologies and their impacts on SC resilience.

Secondly, existing studies concentrate on only a limited subset of the risks likely to emerge in the event of a shock. Health and operational risks dominate the current discourse, with at least seven

Table 1
Studies adopting more than one Industry 4.0 technology to improve the performance of agri-food SCs.

Author	Industry 4.0 Tech	Food Type	Risk Type	Method	Country	Resilience Perspective	Resilience View	Outcome	Impact
Mededjel et al. (2017)	IOT + Cloud computing	NA	Health, Operational	Quantitative/Information systems	United States	Engineering, Social–Ecological	Persistence, Adaptation	Improved traceability	NA
Giagnocavo et al. (2017)	IOT + Big data analytics	Fresh (Horticulture)	Health	Qualitative/Framework	Spain	Engineering, Social–Ecological	Persistence, Adaptation, Transformation	Improved traceability	Sector-related
Alfian et al. (2017)	IOT + Big data analytics	Fresh	Health	Quantitative/Information systems	South Korea	Engineering	Persistence	Real-time monitoring	Sector-related
Engelseth et al. (2019)	IOT + Big data analytics	Fresh (Banana)	Operational	Qualitative/Case study analysis	Costa Rica	Engineering, Social–Ecological	Persistence, Adaptation	Improved connectivity	Sector-related
Lin et al. (2019)	Blockchain + IOT	NA	Technology	Quantitative/Information system	China	Engineering	Persistence	Improved safety and transparency	NA
Pal and Kant (2019)	Cyber–physical systems + IOT	Fresh (multiple)	Health, Climate	Quantitative/Modelling and simulation	United States	Engineering, Social–Ecological	Persistence, Adaptation	Improved safety and traceability	Sector-related
Abbas and Marwat (2020)	Cyber–physical systems + Big data analytics	NA	Technology	Quantitative/Information systems	Pakistan	Engineering	Persistence	Improved coverage and connectivity	NA
Singh et al. (2018)	Big data analytics + Cloud computing	Fresh (Beef)	Climate	Quantitative/MCDM	United Kingdom	Engineering, Social–Ecological	Persistence, Adaptation, Transformation	Improved decision making	Sector-related, Time-related
Liu et al. (2020)	Blockchain + Big data analytics	Fresh	Health	Quantitative/Modelling and simulation	China	Engineering	Persistence	Improved decision making	Time-related
Fu et al. (2020)	IOT + Big data analytics + Blockchain	Fresh (Beef and Grain)	Health	Qualitative/Case study analysis	China	Engineering	Persistence	Improved security	Sector-related, Time-related
Spadoni et al. (2019)	IOT + Big data analytics + Blockchain	Processed (Wine)	Health, Operational	Qualitative/Case study analysis	Italy	Engineering	Persistence	Improved safety and traceability	Sector-related
Chen (2017)	IOT + Big data analytics + Cyber–physical systems	NA	NA	Quantitative/Information systems	Taiwan	Engineering	Persistence	Improved safety and traceability	NA
This study	*Digital capabilities**	*Fresh and Processed**	*Health, Climate, Geopolitical, Technology*	*Qualitative + Quantitative*	*Australia*	*Engineering, Social–Ecological*	*Persistence, Adaptation, Transformation*	*Improved SC resilience*	*Sector-related, Time-related*

* Combining Industry 4.0 technologies, such as IOT, Big Data Analytics, AI, Cyber-Physical Systems, ICT, and more in various ways to develop digital capabilities for improving resiliency in agri-food SCs. Fresh and processed food sector including Grains, Red Meat, Dairy, Horticulture, Seafood, and Wine.

out of the twelve studies identified in Table 1 addressing these risks. In contrast, risks related to climate change and geopolitical factors are not considered as frequently. This is concerning since shocks that affect agri-food SCs are diverse. Agri-food SCs are vulnerable to global economic fluctuations, international crises, trade disputes, and technological disruptions (Jayaram et al., 2014; Barbosa, 2021; Kumar et al., 2021). Each type of shock can have severe but distinct impacts on agri-food SC resilience, thus a more granular analysis that explores the unique characteristics and effects would be beneficial.

Thirdly, studies often describe the impacts of digital technologies on agri-food SC resilience in broad, generalized terms. Commonly cited benefits included enhanced traceability (Lin et al. 2019), monitoring and safety improvement (Chen, 2017), and improved decision-making (Liu et al., 2020). While these outcomes are important, their general nature prevents a deeper understanding of how digital technologies enhance SC resilience. Observing these impacts in more granular terms — such as identifying sector-specific or time-dependent effects — would provide a richer, more detailed understanding of SC resilience.

2.2. Agri-food SC resilience perspectives

Wieland and Durach (2021) define SC resilience as: "Supply chain resilience is the capacity of a supply chain to persist, adapt, or transform in the face of change" (p. 316). While this definition has similarities with others, recent debates highlight two distinct interpretations of SC resilience (Wieland et al., 2023; Wieland and Durach, 2021; Herburger et al., 2024), engineering-based and social–ecological perspectives.

In the engineering notion of SC resilience, a common assumption is that it is possible to control SCs through systems, processes, and other governance mechanisms. The primary goal of SC resilience in this case is to return the SC to its original state post-shock, that is, to restore its initial equilibrium. This approach aligned closely with persistence-based resilience, emphasizing stability and functionality despite external shocks.

In the social–ecological notion of SC resilience, the SC is an open adaptive system, with only limited control possible, and with a more free-flowing set of interactions between SC members. The primary goal of SC resilience, in this case, is to adapt to emerging, uncertain conditions and to transform from one state to another over time. This perspective underscores the evolving nature of SCs and their capacity to reconfigure in response to disruptions.

The treatment of shocks in existing SC resilience studies (see Table 1) centres on the engineering perspective, while social–ecological perspectives receive less attention. Dealing with SC shocks can involve panic and lead to irrational decision-making (Ali et al., 2017; Ivanov and Dolgui, 2020). This response to shocks by SC member firms tends to promote persistence. Persistence is simple since there are already frames of reference for SC managers to draw on when attempting to restore the status quo and SC managers' beliefs that they can control a situation support action. However, this approach does not account for SCs where managerial control is limited, where SCs are open, adaptive systems, and where the effects of SC shocks are unknown. As such, the SC resilience literature currently lacks a comprehensive account of the adaption and transformation aspects of SC resilience. The present study extends and compares notions of SC resilience by examining persistence, adaptation, and transformation in Australian agri-food SCs.

Persistence, adaptiveness, and transformation represent three distinct but interrelated dimensions of SC resilience, each varying in scope and impact over short- and long-term horizons. Short-term persistence focuses on a system's capacity to absorb shocks and maintain operational continuity through redundancies, buffering mechanisms, and rapid response protocols, while long-term persistence involves institutionalizing structural reinforcements, fortifying security, and embedding risk-mitigation strategies to withstand prolonged uncertainties. Adaptiveness, in the short term, reflects the agility to recalibrate processes, reallocate resources, and leverage dynamic decision-making to mitigate immediate disruptions, whereas long-term adaptiveness signifies an organization's ability to integrate learning mechanisms, anticipate change, and continuously refine operational models in alignment with evolving market dynamics and external pressures. Transformation, as the most radical form of resilience, manifests in the short term through the rapid reconfiguration of SC processes, business models, or production frameworks to navigate paradigm shifts, while long-term transformation extends beyond immediate crises, fostering systemic restructuring, cross-sector.

Building on the distinction between engineering and social-ecological perspectives of SC resilience, the time dimension further differentiates persistence, adaptiveness, and transformation in terms of short-and long-term responses. Short-term persistence reflects the immediate ability of an SC to absorb shocks and maintain stability through pre-established redundancies, rapid adjustments, and crisis response mechanisms. Long-term persistence, however, extends beyond reactive measures, embedding structural reinforcements and institutionalized risk mitigation strategies to withstand prolonged disruptions. Adaptiveness, in the short term, involves agile recalibration and adjusting sourcing strategies to mitigate sudden volatility. In the long term, adaptiveness is characterized by scenario planning and flexible operational models to align with shifting market and environmental conditions. Transformation, as the most radical form of resilience, is limited in the short term to ad-hoc structural modifications, temporary shifts in production, or alternative business models to navigate paradigm shifts. In the long term, transformation drives systemic restructuring, integrating disruptive innovations, decentralizing SC architectures, and fostering cross-sector collaboration to create entirely new operational paradigms. While persistence is often the default reaction to disruptions, this study underscores the importance of distinguishing between short-term stabilization and long-term evolution, particularly in SCs where external conditions continuously reshape industry dynamics.

3. Methodology

This study uses a mixed methods approach, summarized in Table 2, to address two research questions.

The first research question is: *what are the digital capabilities that affect Australian agri-food SC resilience? (RQ1)*. To address RQ1, this study focuses on two sub-objectives and uses specific methods for each. First, the study uses content analysis of industry reports and academic literature to develop the digital capabilities taxonomy and validates these through semi-structured interviews. Second, the study uses a narrative literature review of 120 peer-reviewed academic journal articles to develop a set of SC resilience measures and validates these through a Delphi study. The findings from RQ1 serve as inputs for the subsequent analyses.

The second research question is: *what are the effects of digital capabilities on Australian agri-food SC resilience, considering both the engineering (persistence) and social–ecological (adaptation and transformation) perspectives? (RQ2)*. To address RQ2, this study employs pairwise comparison as a foundational method to capture expert judgments and derive relative importance weights for digital capabilities, which are subsequently used as inputs for two specific analytical methods. First, the study uses network analysis to visualize and quantify connections between digital capabilities and resilience criteria, utilizing the derived weights. The prioritized digital capabilities for short-term resilience are validated through an assessment of network modularity. Second, the study uses system dynamics modelling to simulate the systemic effects of digital capabilities over time, with the findings validated through sensitivity analysis. By integrating the criteria, capabilities, and weights, this method explores feedback loops, cumulative impacts, and the prioritization of digital capabilities for long-term resilience.

In this study, arbitrary time units are employed to analyse the resilience dynamics rather than relying on real-world chronological timelines. This approach allows for a standardized assessment across multiple sectors, ensuring comparability despite sectoral differences in response speed and technological integration. Given that the study does not adopt a longitudinal design, the focus is on modelling general patterns of resilience rather than tracking real-world resilience over extended periods. It is also linked to the diverse life cycle of digital capabilities. A quantile-based approach is used to divide the arbitrary time scale into short-term and long-term periods in a systematic and consistent manner. By using quantiles, we avoid subjective cutoffs and instead create a data-driven division where each phase (short-term and long-term) represents an equal portion of the overall timeline. This ensures that trends, shocks, and long-term effects are analysed in a structured and repeatable way.

The study centres on six Australian agri-food SCs: Grains, Red Meat, Dairy, Horticulture, Seafood, and Wine. We selected these sectors due to their significant economic contributions, diverse SC structures, and varying levels of digital adoption, and to provide a comprehensive representation of Australia's agri-food SC landscape. The grains sector, Australia's largest agricultural export earner, contributed AU$13.8 billion to exports in 2020–21 (ABARES, 2022), exemplifying complex global SCs and leading in precision agriculture adoption. Red meat, with exports valued at AU$18.4 billion in 2021 (MLA, 2022), and dairy, contributing AU$3.3 billion in export earnings (Dairy Australia, 2021), both face unique challenges in traceability and cold chain management. Horticulture, generating AU$11.9 billion in production value (HORT Innovation, 2021), presents distinct opportunities for digital innovation in quality control and logistics due to its perishable nature. The seafood sector, vital to coastal economies with a production value of AU$3.1 billion (FRDC, 2022) and wine, exporting AU$2.8 billion annually (Winetitles, 2022), provide perspectives on how digital capabilities could support product differentiation and resource management. Collectively, these sectors accounted for over 70% of Australia's total agricultural exports in 2021 (DFAT, 2022).

3.1. Developing the digital capabilities taxonomy and identifying resilience measurement criteria in Australian agri-food SC—addressing RQ 1

3.1.1. A taxonomy of digital capabilities

To develop the digital capabilities taxonomy, the study involved a content analysis (Burnard, 1995; Bengtsson, 2016) of a diverse set of industry reports from reputable Australian organizations, including the Food Agility CRC and KPMG (Food Agility CRC and KPMG Australia, 2022), the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES, 2020, 2021), the Business Continuity Institute (BCI, 2021), and Department of Agriculture Fisheries and Forestry (DAFF, 2020a,b). Additional sources included reports from the Commonwealth Scientific and Industrial Research Organization (Robertson et al., 2018), Australian Government Department of Industry, Science and Resources (Department of Industry, Science and Resources, 2022), and the House of Representatives Standing Committee on Agriculture (House of Representatives Standing Committee on Agriculture, 2022).

The selection criteria prioritized reports that focused on agri-food sectors, digital technologies, and their applications to operational challenges and opportunities. Reports published within the last decade were included, with a preference for those addressing Australian contexts while incorporating global insights selectively. Relevance, credibility, and availability were key factors in the selection process. When necessary, academic publications referenced within these reports (Taghikhah et al., 2023; Ng et al., 2022) were reviewed to supplement and validate findings. This approach ensured the dataset included diverse and high-quality perspectives, combining practical insights from industry reports with targeted academic contributions.

The content analysis began by mapping various SC shocks — such as health hazards, droughts, natural disasters, and geopolitical events — to different agri-food sectors, and by identifying the resultant challenges and opportunities from each SC shock (refer to Appendix B.1 for detailed analysis). Using thematic, selective, and axial coding (Ryan and Bernard, 2003), we organized the data into coherent categories of digital capabilities. The process involved:

- Thematic Coding: Identifying overarching themes based on the primary functions, technological domains, and impacts of digital technologies on resilience.
- Selective Coding: Allocating related digital technologies, systems, and resources into these broader categories of digital capability.
- Axial Coding: Analysing relationships between the capabilities, including synergies, complementarities, and integration points.

Table 2
Methodological framework for analysing digital capabilities and their impacts on Australian agri-food SC resilience.

RQ	Main purpose	Data requirement	Analysis method	Main outputs	Validation method	Justification of application
RQ1	Developing a taxonomy of digital capabilities	Industry reports and relevant academic articles	Content Analysis	#Digital resilience capabilities taxonomy	Semi-Structured Interviews	Synthesizing insights from diverse sources
	Identifying criteria SC resilience measures	Peer-reviewed articles from the Web of Science	Narrative Literature Review	#Socio-ecological resilience criteria	Delphi Method	Understanding of existing resilience criteria
RQ2	Deriving relative importance weights	#Digital capabilities and #Resilience criteria	Pairwise Comparison	#Relative importance weights	Consistency Ratio	Eliciting expert judgments to inform subsequent analyses
	Prioritizing digital capabilities adoption in short-term	#Digital capabilities and #Resilience criteria and #Relative importance weights	Network Analysis	#Immediate digital capabilities for SC resilience enhancement	Network Modularity	Mapping interconnections among capabilities
	Prioritizing digital capabilities adoption in long-term	#Digital capabilities and #Resilience criteria and #Relative importance weights	System Dynamics	#Strategic digital capabilities for SC resilience enhancement	Sensitivity Analysis	Capturing systemic feedback loops and accumulative effects

The iterative process resulted in a preliminary taxonomy which categorizes digital technologies into digital capability areas relevant to SC resilience.

To refine and validate the preliminary taxonomy, the study employed semi-structured interviews. A panel of sixteen experts from the Australian agri-food industry provided their insights. Selection criteria included a minimum five years of experience in Australian agri-food SC management, at least three publications in reputable journals on related topics, and experience in implementing or overseeing digital technologies in SCs (refer to Appendix A.1 for a summary of expert profiles). The experts were identified through professional networks, industry collaborations, and academic connections, particularly with the Australian Food Agility CRC.

The process followed these steps:

1. Round One: Academic experts (E10, E11, E13, E14 and E16) reviewed the preliminary taxonomy and provided feedback on the categories, relevance, and coherence of digital capabilities.
2. Consensus Building: We calculated inter-rater reliability using Gwet's coefficient (Gwet, 2001) to measure agreement among the experts on the categorization of digital capabilities. This coefficient was chosen over Cohen's kappa due to its robustness in situations where marginal distributions were unbalanced, which can cause kappa to underestimate agreement. The formula for Gwet's AC1 is given in Eq. (1):

$$AC1 = \frac{P_o - P_e}{1 - P_e} \tag{1}$$

   where P_o is the observed agreement proportion and P_e is the expected agreement proportion, calculated based on rater marginal probabilities.
3. Refinement: Based on expert feedback, we refined the taxonomy, consolidating overlapping categories and adding missing elements to ensure comprehensiveness and practical utility.

To further validate the taxonomy, we conducted additional semi-structured interviews (Mason, 2002) with four panel experts (E05, E06, E07, and E08). These online interviews, lasting approximately 30 min each, combined structured questions with open-ended discussions to allow in-depth exploration of emergent themes and validate the taxonomy's relevance to real-world SC challenges (details in Appendix A.2).

3.1.2. Identifying SC resilience criteria

There has been a lack of standardization in SC resilience criteria and terminology, making benchmarking and comparative analysis difficult (Poulin and Kane, 2021). Recent work by Bruckler et al. (2024) proposed 17 resilience criteria that describe the characteristics of the resilience curve, signalling a shift towards more holistic evaluations. While these advances are promising, they do not account for the nuances of the Australian agri-food sector. To address this gap, this study involves a narrative literature review (Green et al., 2006) using peer-reviewed journals indexed in the Web of Science database, including sources such as International Journal of Production Research, Ecological Indicators, Journal of Agriculture and Food Research, Agricultural Systems, etc. The search strategy employed Boolean operators with key terms such as "supply chain resilience," "agri-food supply chain/network/system," "resilience capacity," "resilience metrics," and "risk mitigation strategies." Papers were screened based on their title, abstract, and keywords, resulting in the selection of 120 articles relevant to resilience measurement (article details are in Appendix 2). While not all selected articles focused exclusively on Australian agri-food SCs, they were included due to their potential applicability to the agri-food context. This approach allowed us to incorporate insights from the broader SC resilience literature, including studies on adjacent sectors with similar characteristics, such as perishable goods, complex distribution networks, or environmental susceptibility.

To refine, compile, and validate the identified resilience criteria, we conducted a Delphi study (Okoli and Pawlowski, 2004) using expert voting as the primary data collection mechanism (Stenbro, 2010). This qualitative method was widely employed to achieve consensus on specific concepts through the expertise and experience of a knowledgeable panel. Our expert panel, whose profiles were detailed in Appendix A.1, was trained on the study requirements and voting process. They were briefed on the objectives of the voting exercise and its role in identifying and ranking the most critical resilience criteria.

The Delphi process consisted of two rounds to ensure iterative refinement and collective judgment. In the first round, experts rated each resilience criterion on a 3-point Likert scale (1 = not important/relevant, 3 = highly important/relevant). In the second round, the experts reviewed the aggregated results from the first round and had the opportunity to revise their ratings based on group feedback. For each criterion i, with n votes, the mean score M_i was calculated using Eq. (2):

$$M_i = \frac{1}{n}\sum_{j=1}^{n} V_{ij} \tag{2}$$

where V_{ij} represents the vote of the jth expert for the ith criterion. These outputs formed the foundation for advancing to the next phase of the study, where they were used as criteria for pairwise comparison, and constitute nodes for network analysis, and stocks for system dynamic modelling.

3.2. Prioritizing digital capabilities for short and long-term resilience in Australian agri-food SCs—addressing RQ 2

3.2.1. Deriving relative importance weights for digital capabilities

To capture expert judgment regarding the relative importance of digital capabilities for SC resilience, the pairwise comparison method (Kuo and Chen, 2023; Saaty, 1990) was used. This method was particularly valuable as it quantified expert opinions, providing structured, numerical inputs for the subsequent analyses. This process involved: (i) pairwise comparisons of digital capabilities (derived from Section 3.2.1) relative to each resilience criterion and sub-criterion (derived from Section 3.1.2); (ii) pairwise comparisons of digital capabilities with one another; and (iii) pairwise comparisons of resilience criteria and sub-criteria with one another.

These comparisons were conducted through a structured survey distributed to a panel of experts, whose profiles are detailed in Appendix A.1, leveraging their professional insights and judgment. The surveys facilitated pairwise comparisons of elements according to a single criterion at a time, using a standard scale from 1 to 9, where: 1 = Equal importance, 3 = Moderate importance, 5 = Strong importance, 7 = Very strong importance, and 9 = Extreme importance (details were presented in Appendix C.1).

Prior to distribution, a pilot test was conducted with our research team to validate the survey structure and content. The finalized surveys were then distributed to the expert panel, with each expert completing at least three sector-specific surveys, resulting in 55 complete responses and an average of 9 responses per sector.

To ensure data quality, we systematically collected expert opinions and verified that the input matrices were both complete and consistent. Consistency Ratio (CR) calculations confirmed the reliability of the pairwise comparisons, with all matrices achieving a CR value below 0.1, indicating robust and consistent judgments. The weights from these comparisons served as essential inputs for subsequent methods, including weighting edges in network analysis and parametrizing the stock-flow model in system dynamics modelling.

3.2.2. Assessing the impacts of digital capabilities on SC resilience in the short-term

The study applies network analysis (West et al., 2001) to evaluate the impact of digital capabilities on the SC resilience in the short-term due to its ability to uncover systemic interactions and interdependencies. This method offers insights into the roles of key nodes (digital capabilities) in facilitating persistence, adaptation and transformation. Specifically, it identified hubs — highly connected capabilities critical for maintaining system cohesion — whose failure could severely impair the SC's resilience. In addition, network analysis provided critical insights into redundancies and alternative pathways within the network and captured the relational aspects of resilience that were difficult to address through hierarchical or linear methods.

The network was constructed with nodes representing digital capabilities and resilience criteria (derived from Section 3.1.1 and Section 3.1.2), while edges were parametrized based on relative importance weights (Section 3.2.1), reflecting the strength of influence or interaction between nodes. These weighted relationships formed the foundation for analysing how digital capabilities contribute to SC resilience.

To identify the most influential digital capabilities within the network, we employed the weighted degree measure, which calculated the total strength of a node's connectivity by summing the weights of both incoming and outgoing edges. Mathematically, for a graph $G = (V, E)$, where V is the set of nodes and E is the set of edges, each edge $e(i, j) \in E$ has a weight $w(i, j)$. The weighted degree $W_D(v)$ for a node $v \in V$ is expressed in Eq. (3):

$$W_D(v) = \sum_{(v,u)\in E} w(v, u) + \sum_{(u,v)\in E} w(u, v) \quad (3)$$

The first term sums the weights of all outgoing edges from v, representing the influence the node exerts, while the second term sums the weights of all incoming edges to v, representing the influence the node receives. This measure was critical for understanding how digital capabilities interact within the network, particularly in planning and prioritizing resilience through adaptive processes. To ensure comparability of digital capabilities' contributions to resilience criteria, we normalized the weighted degree values using min–max scaling:

$$W_D^{norm}(v) = \frac{W_D(v) - \min(W_D)}{\max(W_D) - \min(W_D)} \quad (4)$$

where $W_D(v)$ is the weighted degree centrality of node v, and $\max(W_D)$ and $\min(W_D)$ are the maximum and minimum weighted degree values, respectively.

To validate the results and assess the network structure, we used the modularity measure, which quantified the strength of division into communities (Newman, 2006). Modularity Q is defined in Eq. (5):

$$Q = \frac{1}{2m} \sum_{(ij)} \left[A_{ij} - \frac{K_i K_j}{2m} \right] \delta(c_i, c_j) \quad (5)$$

Here, m is the total number of edges, A_{ij} is the adjacency matrix, K_i is the degree of node i, and $\delta(c_i, c_j)$ equals 1 if nodes i and j belong to the same community and 0 otherwise. Modularity values (ranging from −1 to 1) above 0.3 generally indicated a significant community structure (Newman and Girvan, 2004), suggesting a robust organization of digital capabilities and resilience criteria into distinct yet interconnected modules.

3.2.3. Assessing the impacts of digital capabilities on SC resilience in the long-term

To assess the impacts of digital capabilities on SC resilience in the long-term, the study utilized system dynamics modelling (Forrester, 1995) because it uniquely captures the dynamic, systemic, and iterative nature of resilience. It simulated how changes propagate through a system over time, reflecting the structural and systemic shifts required for long-term performance. A key strength of this method is its ability to incorporate feedback loops — both reinforcing and balancing — which were essential for modelling how digital capabilities interacted and their impacts evolved over time. Additionally, it assessed the delayed and cumulative effects of digital capability implementation, reflecting how they often require time to materialize, and further provided insights into tipping points, allowing us to identify when incremental investments in digital capabilities lead to significant systemic changes.

The system dynamics model used the resilience criteria from Section 3.1.2 as stocks, representing the accumulation of resistive, adaptive, and transformative capacities over time. The digital capabilities from Section 3.1.1 were modelled as flows, influencing the rates of change in these stocks. This approach demonstrated how the adoption of specific digital capabilities (e.g., SecureData Capability) dynamically influenced resilience criteria, ensuring consistency between the short-term prioritization from network analysis and the long-term prioritization predicted by system dynamics.

The flows were parametrized using the relative priority weights derived from pairwise comparisons in Section 3.2.1, seamlessly integrating expert-driven insights into the simulation model. To ensure robust, sector-specific insights, we developed separate but structurally similar models for each of the six agri-food sectors (grains, horticulture, dairy, red meat, seafood, and wine). This enabled us to compare the dynamic impacts of digital capabilities across sectors while accounting for their unique characteristics. Further details of the modelling process are provided in Appendix C.2.

To validate our model and assess its robustness, we conducted a sensitivity analysis comprising three key approaches. First, we introduced parameter variations of ±10% and ±20% to evaluate how changes in individual parameters influenced the overall resilience scores. This allowed us to assess the stability of the model under varying conditions and ensured that minor perturbations did not result in disproportionate or erratic shifts in output. Second, we tested the model under extreme input scenarios, subjecting it to conditions far outside the typical operating range. This approach assessed whether the model could exhibit reasonable and logical behaviour even under stress, ensuring it did not produce unrealistic or unstable results when parameters were pushed to their limits. Finally, we conducted structural validation by removing key feedback loops within the model. Feedback loops represent the iterative and dynamic mechanisms critical for resilience, and their removal provided insights into how the absence of these mechanisms influenced model outputs over time.

4. Results

4.1. The digital capabilities taxonomy and the SC resilience measurement criteria—addressing RQ 1

4.1.1. The digital capabilities taxonomy

Table 3 presents the digital capabilities taxonomy. The digital capabilities represent 25 digital technologies identified through the content analysis (which are summarized in Appendix B.2). The Gwet AC1 scores from the semi-structured interviews for the taxonomy demonstrate a high level of expert agreement, which validates the taxonomy. There were notable scores across key digital capabilities SC resilience. For instance, DS01 and DS09 achieved high scores of 0.81 and 0.88, respectively, underscoring their critical role in A1 and A4. Commentary on each digital capability follows below.

LogisticsTech (A1) is the first digital capability to emerge from the analysis. This underscores the significance of technologies to optimize and automate SC operations, with a focus on logistics networks, resource management, and real-time monitoring. This capability enables SC managers to streamline routing, scheduling, and workforce allocation through predictive analytics and algorithmic optimization. It supports the integration of IoT sensors, GPS tracking, and cloud-based platforms for real-time visibility of SC activities. It facilitates dynamic adjustments to disruptions, such as rerouting shipments or reallocating resources. Additionally, it plays a pivotal role in cold chain logistics by monitoring temperature-sensitive products to maintain quality and compliance with safety standards.

SecureData (A2) is also a prominent digital capability to emerge from the analysis, which focuses on ensuring robust data governance, integration, and interoperability within SC ecosystems, while maintaining stringent security and compliance with regulatory standards. This capability leverages technologies such as blockchain, secure APIs, and encryption protocols to safeguard sensitive information and enhance traceability. It enables seamless data sharing among stakeholders, allowing for rapid recall management, contamination tracking, and adherence to food safety protocols. SecureData also supports predictive risk management by enabling SC participants to monitor, analyse, and mitigate vulnerabilities, such as cyber threats or supply disruptions, through comprehensive data insights. Its role extends to enhancing trust and transparency across SC stakeholders.

ClientValue (A3) was a critical digital capability to emerge from the analysis. It focuses on integrating customer insights, market analysis, and product quality management to enhance SC performance. At its core, this capability leverages customer data and behavioural analytics to understand evolving market trends, consumer preferences, and demand patterns. It facilitates tailored product offerings and personalized services that align with customer expectations, building long-term loyalty and competitive advantage. ClientValue also emphasizes robust product quality assurance systems, ensuring consistency and compliance with industry standards across all stages of the SC. This capability creates a symbiotic relationship where customer feedback informs continuous improvement processes, enabling organizations to fine-tune production, packaging, and distribution strategies to align with market demands.

InsightDecision (A4) was another important digital capability to emerge from the analysis. This digital capability represents the use of decision-support systems and digital twins to enable data-driven strategies and informed operational planning within the SC. It integrates technologies like analytical algorithms, predictive tools, and scenario analysis to identify trends, anticipate disruptions, and optimize resource allocation. It allows SCs to simulate complex supply–demand dynamics, evaluate alternative strategies, and implement actionable insights efficiently. Additionally, it incorporates dynamic tools such as pricing algorithms and demand forecasting to align operational outputs with fluctuating market conditions. InsightDecision ensures that SC managers can preemptively address uncertainties and make informed decisions based on accurate, actionable intelligence, minimizing reactive inefficiencies and maximizing operational performance.

InnovateTech (A5) emerged as a foundational digital capability, representing the strategic anticipation, adoption, and integration of transformative technologies designed to reshape and future-proof agri-food SCs. This capability emphasizes building adaptive system architectures that allow seamless incorporation of speculative innovations, enabling the industry to remain responsive to technological advancements and market shifts. At its core, InnovateTech promotes the establishment of scalable frameworks that facilitate incremental and systemic technological upgrades while ensuring compatibility across interconnected systems. Furthermore, it prioritizes speculative experimentation, enabling agri-food organizations to explore untested technological applications and evaluate their potential impact. It advocates for a culture of strategic foresight to ensure a proactive rather than reactive approach to innovation.

4.1.2. Agri-food SC resilience assessment

Informed by an extensive literature review, this study identifies a comprehensive inventory of resilience criteria and sub-criteria, which are detailed in Appendix B.4. Inspired by the resilience framework outlined in Wieland and Durach (2021) and in Bruckler et al. (2024), we categorized these criteria into three key capacities—Resistive Capacity, Adaptive Capacity, and Transformative Capacity. To validate and refine these criteria and associated sub-criteria, we conducted a Delphi study for two rounds ensuring that they align with the practical and theoretical demands of Australian agri-food SCs.

The synthesized findings presented in Table 4 highlight the distinctions across engineering and social–ecological resilience perspectives. The engineering perspective was reflected in Resistive Capacity (C1), which included sub-criteria such as Risk Awareness (C1-1) (Liu and Wang, 2020) (which measures the identification and mitigation of potential risks), Resistive Duration (C1-2) (Yang et al., 2018) (which gauges the time between hazard onset and the start of disruption), and Built-In Redundancy (C1-3) (Aghababaei et al., 2021) (which evaluates the availability of alternative resources or systems to ensure functional continuity).

In contrast, the social–ecological perspective extends resilience to include adaptation and transformation. The Adaptive Capacity (C2) criteria focused on the ability of systems to respond flexibly and recover effectively. Sub-criteria such as Flexibility (C2-1) (Ojha et al., 2018) captures the availability of contingency plans and alternative

Table 3
A taxonomy of digital capabilities for Australian agri-food SC resilience.

Digital capability group	Definition	Digital Capability Sub-Group	Gwet's AC1	Example
A1: Supply Chain Network Design: *LogisticsTech Capability*	Involves the use of advanced technologies for the optimization and automation of supply chain operations, including routing, scheduling, network design, and workforce allocation. These technologies improve the efficiency of logistics through data-driven decision-making, predictive analytics, and automated processes.	1. SC Network Optimization (DS01) 2. SC Operations Management (DS03) 3. Automation and Labour Efficiency (DS12)	1. DS01 = 0.81 2. DS03 = 0.78 3. DS12 = 0.85	Robotics Process Automation (RPA) in logistics can automate repetitive tasks, simplify operations, improve data collection practices, and reduce human errors. UiPath is a leading provider of RPA for SC procurement, order processing, and inventory management.
A2: Data Management and Security: *SecureData Capability*	Focuses on the governance, integration, and secure management of data across systems and stakeholders. This includes ensuring data interoperability, regulatory compliance, and protection against breaches. Technologies like blockchain and secure APIs enhance data accuracy, traceability, and confidentiality.	1. Data Governance and Security (DS02) 2. Data Integration and Interoperability (DS06) 3. Data Regulatory Compliance (DS07)	1. DS02 = 0.83 2. DS06 = 0.80 3. DS07 = 0.87	Blockchain, IAM systems, and secure APIs can create a comprehensive data management and security solution. IBMFoodTrust is a blockchain-based platform that enhances transparency, prevents data breaches, and ensures integrated data flows.
A3: Customer Relations and Quality Optimization: *ClientValue Capability*	Aims at understanding customer behaviour and market trends through real-time customer insights and predictive analytics. It supports product quality optimization, adaptive pricing strategies, and customer-focused solutions.	1. Customer Engagement and Insights (DS04) 2. Product Quality Management (DS08)	1. DS04 = 0.82 2. DS08 = 0.79	SalesforceCustomer360 predicts customers' behaviour, guides agile pricing strategies, and offers adaptive value optimization.
A4: Insights and Decision Support: *InsightDecision Capability*	Encompasses tools and methods that facilitate data-driven decision-making through predictive modelling, scenario analysis, and advanced analytics. Helps organizations evaluate multiple strategies, align pricing models, and allocate resources based on actionable insights.	1. Dynamic Pricing and Value Optimization (DS10) 2. Risk-based Decision Support (DS09)	1. DS10 = 0.77 2. DS09 = 0.76	SASAnalytics enables businesses to evaluate scenarios, anticipate risks, and navigate disruptions. InforSCM provides SC management software for planning and decision support. Expana offers market intelligence services.
A5: Innovation and Technology Integration: *InnovateTech Capability*	Centers on the forward-looking development and integration of transformative technologies to reimagine SCs. Emphasizes anticipating technological breakthroughs, fostering adaptive architectures, and enabling seamless incorporation of innovations.	1. Technology Integration (DS05) 2. Innovation (DS11)	1. DS05 = 0.79 2. DS11 = 0.84	Electro-agriculture utilizes electrical energy to enhance plant growth. Lectrolyst converts carbon and water into acetate, enabling plant growth without direct photosynthesis.

strategies, while Recovery Rate (C2-2) (Liu and Wang, 2020) assesses the speed of functional restoration following a disruption. Additionally, Connectivity (C2-3) (Wieland et al., 2023) evaluates the effectiveness of multi-level partnerships in facilitating and the proportion of independent modules in the SC network. These sub-criteria reflect the adaptive nature of social–ecological systems, emphasizing the need for agility and coordination in the face of uncertainty.

Transformative Capacity (C3) addresses the ability to innovate and restructure systems post-disruption. Sub-criteria such as System Scalability (C3-1) (Wang and Koren, 2012) measure the number and timeliness of improvements implemented after a disruptive event, Governance (C3-2) (Wieland et al., 2023) captures the degree of decentralized decision-making and stakeholder inclusion in the restructuring process, and Learning Rate (C3-3) (Wieland et al., 2023) evaluates the rate of

Table 4
Key resilience criteria and sub-criteria identified in the Australian agri-food SCs.

Resilience Perspective	Engineering	Socio-Ecological	
Resilience Views	Persistence	Adaptation	Transformation
Resilience Criteria	**C1: Resistive Capacity** The ability to resist or absorb shocks while maintaining function.	**C2: Adaptive Capacity** The ability to react quickly and flexibly to change.	**C3: Transformative Capacity** The ability to innovate, evolve, and restructure in response to change.
Resilience Sub-Criteria	**C1-1: Risk Awareness** *The ability to identify risk scenarios and design mitigation plans.* **C1-2: Resistive Duration** *Time from the start of a hazard to the beginning of disruption.* **C1-3: Built-In Redundancy** *Number of alternative resource reserves available for critical functions.*	**C2-1: Flexibility** *The agile capacity to respond to or adjust effectively during disruptions.* **C2-2: Recovery Rate** *Speed of restoring functionality after a disruption.* **C2-3: Connectivity** *Number of multi-level partnerships and modular linkages.*	**C3-1: System Scalability** *The ability to expand, contract, or evolve in response to disruption, including the time required to achieve these changes.* **C3-2: Governance** *The capacity to manage transitions through decentralized and inclusive decision-making structures.* **C3-3: Learning Rate** *The ability to learn and implement radically new technologies, policies, and practices.*

adoption of new technologies, policies, or practices. Together, these sub-criteria represent the transformative nature of SC resilience, highlighting the need to build forward better in the aftermath of disruption.

4.2. The impacts of digital capabilities on persistence, adaptation, and transformation in Australian agri-food SCs—addressing RQ2

4.2.1. Prioritized digital capabilities for Australian agri-food SC resilience in short-term

The network illustration derived from the network analysis in Fig. 1 provides an abstract representation of the structural interrelationships between digital capabilities, resilience criteria, and sub-criteria, offering insights into the prioritization for short-term resilience within Australian agri-food SCs.

The pairwise comparison approach was employed to parametrize network edges through constructing matrices for three four levels: comparisons among resilience criteria (C1–C3), comparisons between sub-criteria within each primary criterion (C1-1–C3-3), comparisons between digital capabilities and their alignment with resilience criteria (A1–A5), and self-effects within each element. Self-effects were incorporated along the diagonal of the matrices, representing the standalone influence or intrinsic strength of each element independently of their relationships with other elements. These matrices were normalized by dividing each element by the sum of its respective column. The relative weights for each element were derived as the row-wise averages of the normalized values (details in Appendix D.1).

Appendix D.2 presents the details of sector-specific network structures along with their modular values and identifies commonalities. All modularity values exceeded the critical threshold of 0.3 (Kim et al., 2015), demonstrating that the networks are not random but structured in a way that supports actionable and practical insights for enhancing adaptation.

Table 5 presents the normalized weighted averages of digital capability nodes across the six agri-food SC sectors. These values were derived from the specific network structures of each sector and provide a quantitative measure of the influence and centrality of each digital capability in supporting resilience as adaptation.

From the engineering perspective of resilience, *LogisticsTech Capability (A1)* is the most preferred capability for improving SC persistence in the short term across all Australian agri-food sectors. The findings indicate that it is highly effective in maintaining SC continuity during disruptions, particularly in sectors where time sensitivity and logistics complexity are critical (Ali et al., 2021). For example, Dairy, Seafood, and Red meat sectors rely heavily on cold-chain logistics to maintain product quality and safety during transport. Short-term disruptions such as power outages, road blockages, or equipment failures can jeopardize the entire SC, leading to spoilage and financial losses. For example, the collapse of Scott's Refrigerated Logistics in March 2023 led to significant disruptions in Australia's cold chain logistics (ABC News, 2023). The company, which was a major provider of refrigerated transport services, entered liquidation, leaving about $500 million worth of frozen and chilled food in limbo within its warehouses. In response to this collapse, major supermarket chains, including Coles and Woolworths, used *LogisticsTech* to redistribute logistics contracts to alternative providers.

From a socio-ecological perspective of resilience, the results demonstrate that *InsightDecision Capability (A4)* and *InnovateTech Capability (A5)* are critical for driving short-term adaptation and transformation across Australian agri-food sectors, respectively. The former enables rapid, informed decision-making to adapt to immediate disruptions, while the later accelerates the deployment of innovative solutions to transform systems within a short timeframe.

In 2019, Australia's beef industry faced simultaneous challenges from prolonged droughts in key production regions and catastrophic flooding in northwest Queensland MLA (2019). These conditions led to a 7.7% decline in the national herd, the largest drop in decades, and caused major disruptions in Red meat SC. Under these conditions, the application of *InsightDecision* could have provided real-time market intelligence, pricing data, and predictive analytics to navigate volatile supply and demand. With feedlots at near capacity and feed prices rising, decisions making tools could model the financial impacts of sourcing supplementary feed versus reducing herd size or strategically time their sales to capitalize on this demand while managing constraints.

In 2022–23, Australian horticultural producers faced significant crop losses due to adverse weather events, which accounted for 63% of total crop loss and waste. However, instead of allowing these losses to result in wasted resources, producers demonstrated short-term transformation through adopting *InnovateTech* to repurpose waste into valuable

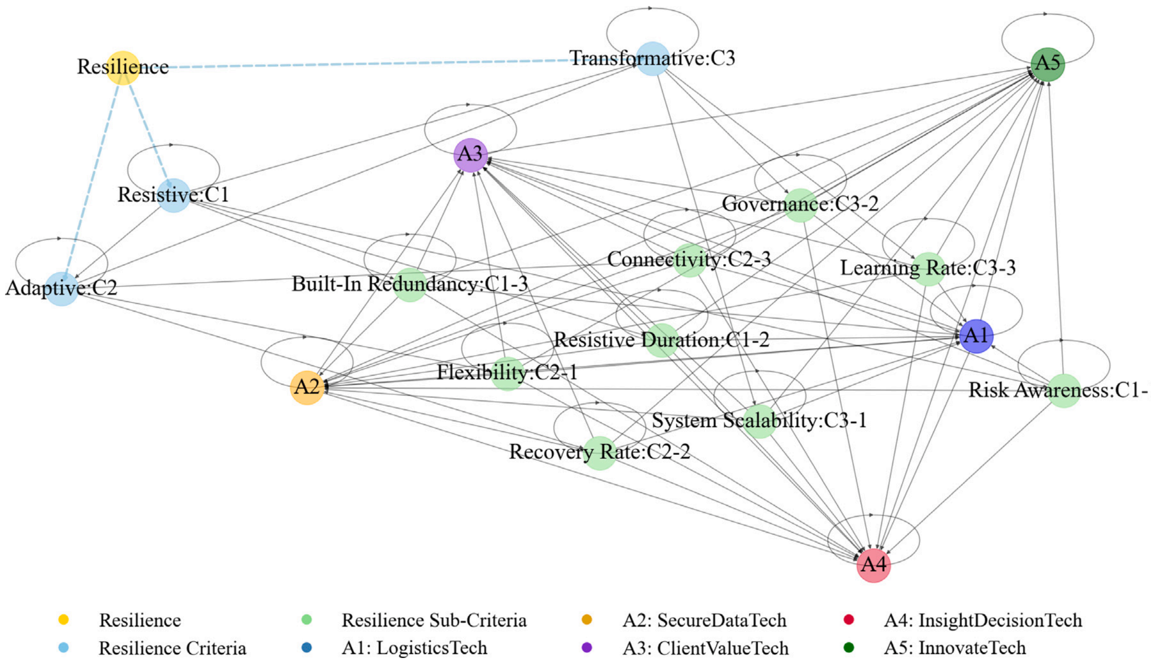

Fig. 1. Network structures presenting the relationships among digital capabilities, resilience criteria, and sub-criteria, for short-term resilience prioritization in Australian agri-food SC.

Table 5
Normalized weighted average degree of digital capabilities for short-term resilience across engineering and socio-ecological dimensions in Australian agri-food SC.

		Grains			Red Meat			Dairy		
		C1 Resistive	C2 Adaptive	C3 Transformative	C1 Resistive	C2 Adaptive	C3 Transformative	C1 Resistive	C2 Adaptive	C3 Transformative
A1	*LogisticsTech Capability*	**0.30**	0.18	0.06	**0.26**	0.15	0.05	**0.28**	0.22	0.08
A2	*SecureData Capability*	0.15	0.14	0.14	0.17	0.12	0.13	0.17	0.18	0.15
A3	*ClientValue Capability*	0.17	0.20	0.10	0.19	0.22	0.09	0.18	0.21	0.11
A4	*InsightDecision Capability*	0.05	**0.26**	0.12	0.07	**0.24**	0.15	0.22	**0.24**	0.14
A5	*InnovateTech Capability*	0.02	0.05	**0.20**	0.05	0.08	**0.18**	0.15	0.12	**0.20**
		Seafood			Horticulture			Wine		
A1	*LogisticsTech Capability*	**0.25**	0.16	0.04	**0.28**	0.20	0.05	**0.27**	0.18	0.03
A2	*SecureData Capability*	0.18	0.14	0.12	0.16	0.16	0.11	0.15	0.14	0.14
A3	*ClientValue Capability*	0.19	0.20	0.10	0.18	0.28	0.08	0.17	0.21	0.12
A4	*InsightDecision Capability*	0.20	**0.24**	0.16	0.22	**0.30**	0.18	0.22	**0.25**	0.15
A5	*InnovateTech Capability*	0.16	0.10	**0.19**	0.13	0.18	**0.22**	0.14	0.10	**0.17**

by-products such as compost and animal feed. This resulted in approximately 10% of horticultural crop loss per farm was recovered for alternative uses, a significant increase from just 2% in 2021–22. Apple, banana, and citrus producers led the way, with 20% of crop loss/waste per farm being recovered and utilized (F. A. F. Department of Agriculture, 2024). Additionally, on-farm composting systems and partnerships with livestock feed companies were established in a matter of weeks to reduce waste while creating new revenue streams.

Other important network features include self-looping feedback and modularity values. The self-loop weight of *InsightDecision* (0.8) signifies its inherent strength and ability to independently generate actionable, data-driven insights, suggesting that its integration into decision-making processes can substantially enhance short-term adaptability without relying heavily on external inputs. For sector-specific modularity, higher modularity values in Grains (0.33) and Red Meat (0.32) indicate that these sectors can leverage digital capabilities more effectively to optimize their internal operations and isolate disruptions, thereby enhancing short-term resilience. Conversely, the lower modularity in Dairy (0.316) and Seafood (0.313) suggests more interconnected SC networks which amplify the impact of disruptions, as shocks in one part of the network are more likely to propagate across the entire system. Thus, supplementary capabilities may be required to address these systemic vulnerabilities and reinforce resilience in the short term.

4.2.2. Prioritized digital capabilities for Australian agri-food SC resilience in long-term

The sensitivity analysis results generated through the system dynamics modelling presented in Appendix D.3 highlight the stability and robustness of the model under varying conditions, reflecting its ability to capture the complex dynamics of agri-food SCs. Parameter variations of ±10% and ±20% had limited impacts on model outputs,

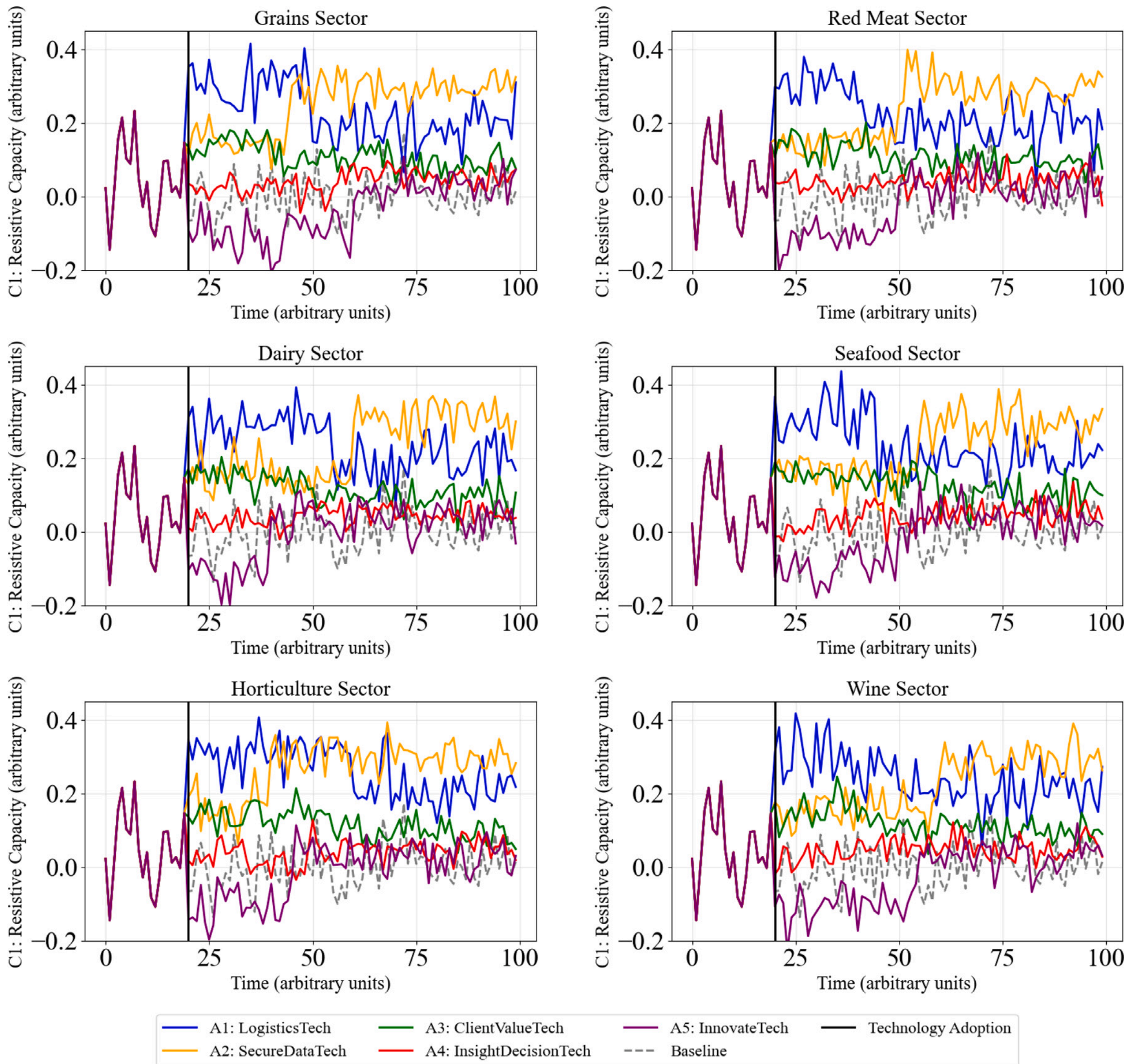

Fig. 2. Simulation results demonstrate the priorities of digital capabilities adoption for long-term resilience (engineering focused) as persistence across Australian agri-food sectors.

with all digital capabilities maintaining stability. *ClientValue Capability (A3)* shows the highest sensitivity (±25%), emphasizing its reliance on precise calibration, while *InsightDecision Capability (A4)* demonstrates moderate but consistent influence, underscoring its localized robustness in the model. The removal of feedback loops reduced contributions by 6%–11%, reaffirming their critical role in sustaining resilience through iterative refinement. Total sensitivity indices, which accounted for interactions, remained bounded below 0.2 across all parameters, ensuring stability even under non-linear behaviours.

The model is designed to capture relative changes rather than being tied to a fixed real-world timeframe, thus an arbitrary unit system is used. This allows for flexibility in comparing different digital capability adoption scenarios while maintaining consistency across sectors. Short-term period (first 50% of the timeline) captures the immediate and transitional effects of technology adoption, whereas long-term period (second 50% of the timeline) reflects the sustained impacts and potential stabilization of resiliency dimensions over time.

Fig. 2 illustrates the priorities of digital capabilities for enhancing long-term resilience across Australian agri-food sectors from an engineering perspective. The general trend indicates that *LogisticsTech Capability (A1)* plays a dominant role in enhancing resistive capacity (C1) and ensuring the continuity of physical operations (e.g., optimizing logistics routes, maintaining inventory flow, etc.) across all sectors in the short term. However, as time progresses, *SecureData Capability (A2)* becomes increasingly critical underscoring the necessity of creating infrastructures for robust data management and secure data sharing systems to stabilize agri-food SCs in the long term.

In May 2021, JBS S.A., the world's largest meat processing company, experienced a ransomware attack that temporarily shut down operations in several countries, including Australia. The attack disrupted slaughterhouses, processing facilities, and SCs, leading to significant operational delays and downstream impacts (Carroll, 2024; Chundhoo et al., 2021). In Australia, cattle slaughter and meat processing were halted for days (Reuters, 2021). Globally, the attack affected nearly 20% of U.S. beef production capacity and caused an estimated market loss of USD 22 billion. The aftermath of the attack saw JBS commit over $USD 200 million to cybersecurity upgrades, blockchain implementation, and real-time data management systems, which have since strengthened the *SecureData* Capability of this SC. Additionally, JBS introduced blockchain-enabled traceability in its Australian operations to securely share data on cattle movements and processing with stakeholders, which enhanced compliance with international export regulations.

Fig. 3 shows the priorities of digital capabilities for enhancing long-term resilience as adaptation view across Australian agri-food sectors. The results highlight that *InsightDecision Capability (A4)* plays a

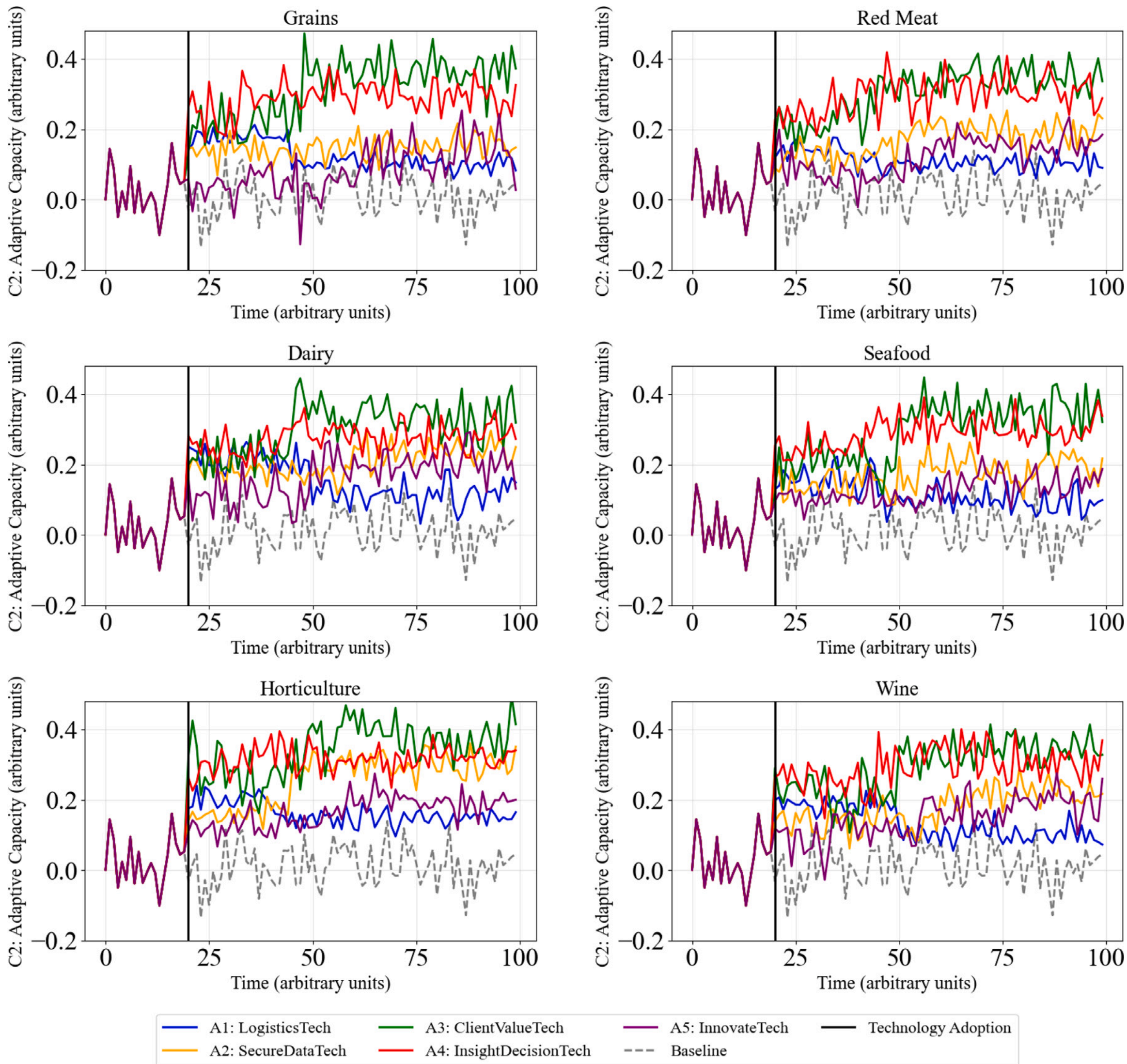

Fig. 3. Simulation results demonstrate the prioritize of digital capabilities adoption for long-term resilience (social–ecological focus) as adaptation across Australian agri-food sectors.

dominant role in short term adaptation, but, over time, its effectiveness is enhanced when combined with *ClientValue Capability (A3)*, forming a feedback loop that integrates customer insights into adaptive strategies. This synergy creates a resilient system capable of continuously aligning operations with evolving market demands (Marusak et al., 2021).

For instance, during the 2021 vintage, Australian wine exports faced significant challenges due to a sharp decline in demand from China (down 92% year-on-year) (Liu et al., 2024). Producers using *ClientValue* could track consumer trends, such as the rising demand for organic and low-alcohol wines, to adjust production strategies (Behzadi et al., 2018; Taghikhah et al., 2020) while *InsightDecision* helped to identify alternative markets, such as the U.S., where exports increased by 9% in value, up to 139 million litres (Winetitles, 2022). This feedback loop between *InsightDecision*'s operational insights and *ClientValue*'s market intelligence allowed the winery to maintain a competitive edge and grow exports in new markets despite adverse conditions. By 2024, the industry had fully recovered, driven by the removal of Chinese tariffs and an increase in exports, particularly to Northeast Asia, which emerged as the largest export region by value, an increase of over 200% (Wine Australia, 2024).

Fig. 4 demonstrates that *InnovateTech Capability (A5)* is consistently the top-ranked digital capability for enabling long-term resilience as transformation across Australian agri-food sectors. Notably, the significance of A5 lies in its ability to simultaneously support reactive transformation in the short term (e.g., addressing immediate disruptions) and strategic transformation in the long term (e.g., fostering sustainability and scalability). This dual impact ensures that systems evolve in response to current challenges while building the capacity to thrive under future uncertainties. The Grains sector, in particular, has seen the application of this capability in scenarios involving climate-related disruptions, highlighting their transformative potential (Zhang et al., 2020).

For instance, hydroponic fodder systems are an innovative solution for producing livestock feed in controlled environments (Ahmed et al., 2018). These systems grow high-quality fodder, such as barley or oats, in vertically stacked trays using nutrient-rich water instead of soil. The ability to produce fresh fodder year-round, regardless of external conditions, makes them particularly effective during periods of feed scarcity caused by disruptions. During the 2019–2020 Australian drought, which significantly increased feed costs and forced many dairy farmers to cull herds, hydroponic systems could have provided a localized and rapid feed source. A typical system can grow up to 25 kg of fresh fodder per square metre per day, using 95% less water compared to traditional methods. Modular hydroponic units can be

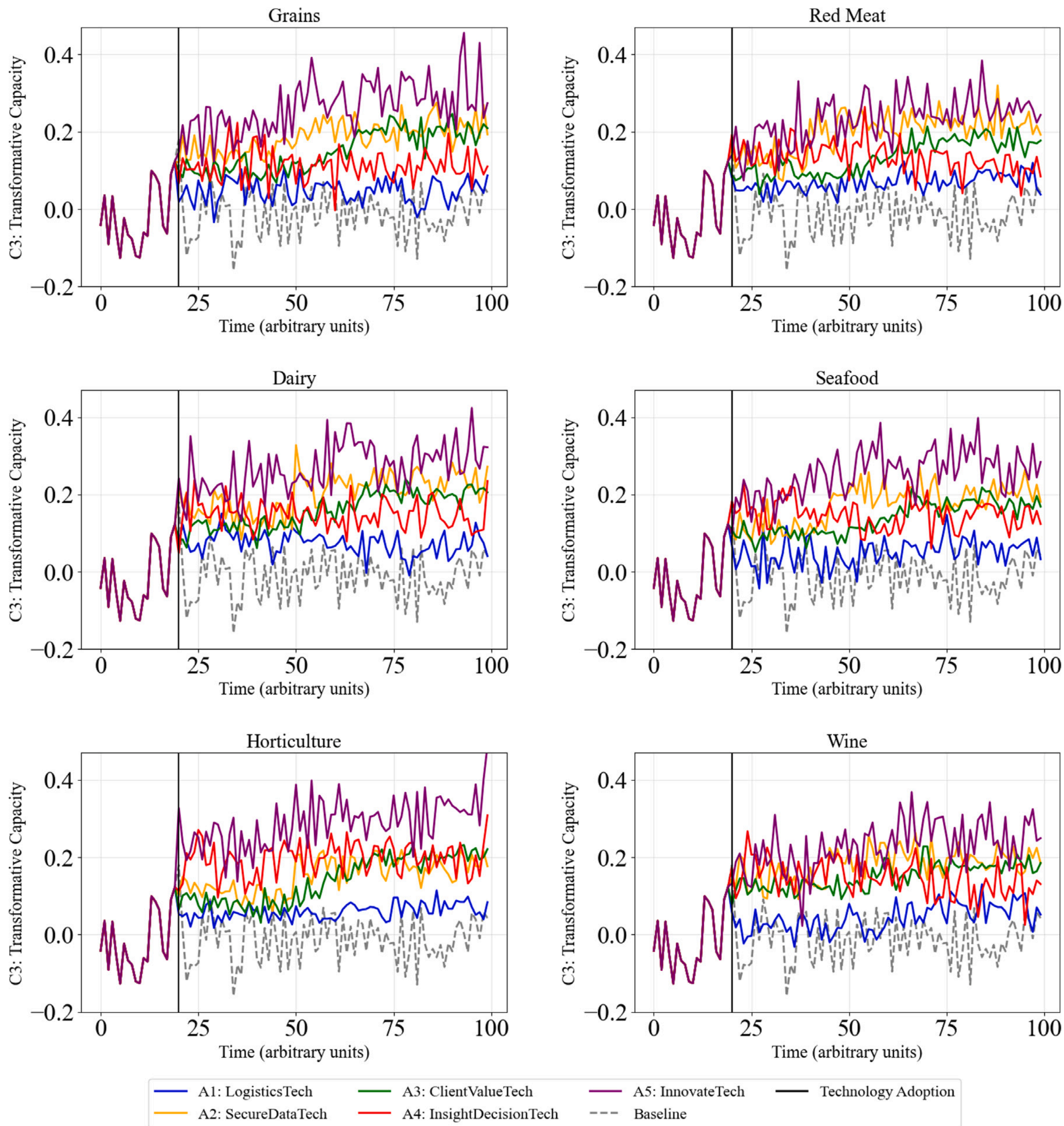

Fig. 4. Simulation results demonstrate the prioritize of digital capabilities adoption for long-term resilience (social–ecological focus) as transformation across Australian agri-food sectors.

operational within weeks, providing a near-instant solution for feed shortages.

Vertical farming presents a transformative solution, especially for the Horticulture sector, in addressing long-term resiliency. By growing crops such as leafy greens, herbs, and berries in vertically stacked layers within controlled environments, vertical farms can insulate production from external shocks (Zhang et al., 2023). This technology ensures year-round production, improved resource efficiency, and proximity to urban markets, making it ideal for perishable horticultural products (Akintuyi et al., 2024). They can produce 390 times more yield per square metre than traditional farms under optimal conditions. Additionally, their controlled environment eliminates risks from pests and weather-related crop failures, allowing producers to maintain market commitments. Vertical farming is more feasible for high-value, short-cycle crops grown near urban centres, where premium pricing can offset higher production costs.

5. Discussion

5.1. Theoretical implications

As Table 1 shows, the current SC resilience literature treats digital technologies as stand-alone resources. For example, machine learning (ML) enables predictive modelling that foresees potential shocks with high accuracy by identifying patterns in historical data (Fosso Wamba et al., 2018; El Jaouhari et al., 2024). Natural language processing techniques analyse text data from various sources (e.g., news reports, social media) to monitor real-time risk developments and flag potential SC disruptions (Janjua et al., 2021). Reinforcement learning helps optimize operational decisions under uncertainty, better preparing SCs to navigate shocks (Ning and You, 2019). Other emerged digital technologies such as IoT (Billah et al., 2023), blockchain (Rathore et al., 2022), and cloud computing (Lu et al., 2022) further enhanced SC

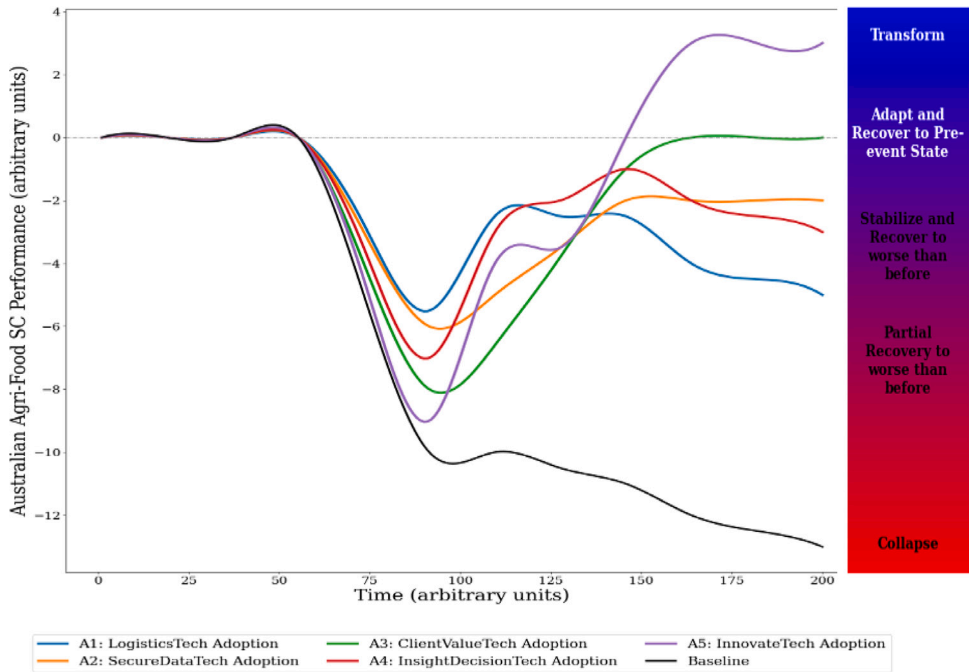

Fig. 5. Demonstration of Australian agri-food SC resilience performance in the short and long term derived from the analysis of digital capabilities and their contributions to persistence, adaptation and transformation aspects.

visibility through improved traceability, and coordination (Rejeb et al., 2019). This leads to a disjointed treatment of digital technologies and one that does not reflect managerial practice.

This study suggests that 'digital capabilities', as combinations of resources through routines, processes and procedures, is a more appropriate theoretical framing when considering the relationship between digital technologies and SC resilience. When facing shocks, it is more likely that SC managers attempt to deploy all resources available to deal with the impending consequences of shocks. Looking at digital technologies as part of a digital capability makes more sense at the firm level and at the SC level. This study involves the development of a novel taxonomy of SC digital capabilities (including LogisticsTech, SecureData, ClientValue, InsightDecision, and InnovateTech), along with a set of criteria to assess them. Through this synthesis, the study addresses the issue of fragmentation in the current digital technology in SC resilience literature while also presenting a robust framework for digital capability assessment.

Current literature also largely ignores the distinction between SC resilience as engineering or social-ecologically focused (Wieland et al., 2023; Wieland and Durach, 2021; Herburger et al., 2024). While digital technology could involve attempts to achieve greater control over a narrowly defined, stable SC, the findings of this suggest that digital technology (as parts of digital capabilities) are also essential to social–ecological SC resilience. We found that digital capabilities are important contributors to agri-food SC persistence, adaptability, and transformation. They can help manage the ordinary operations of SC member firms in their attempts to restore equilibrium by speeding a return to business-as-usual. They can also assist with adaptation to uncertain and evolving circumstances. Digital capabilities can also assist with transformation to a new normal. Hence, digital capabilities have important roles in both engineering and social-ecologically focused SC resilience since they could help sustain current operations while also supporting adaptation and transformation.

This study is one of few to unpack the varying impacts of digital capabilities at different stages of SC resilience. The findings show that not only do digital capabilities cluster as sets of related technologies, systems and processes, but each has different effects on SC resilience over time. Fig. 5 provides a conceptual summary of the findings, showcasing the performance of Australian agri-food SC resilience under a simulated disruption. The trajectories demonstrate that different digital capabilities have varying impacts on resilience outcomes. LogisticsTech shows strong immediate recovery capabilities, stabilizing the SC in the short term but plateauing over time. SecureData enhances long-term stability, preventing collapse through robust data governance and secure operations. InsightDecision performs well in short-term adaptation, enabling agile responses to disruptions, while ClientValue supports gradual recovery aligned with evolving market needs. The transformative power of InnovateTech is evident as it drives the SC toward a state better than its pre-disruption performance, reflecting its role in fostering innovation and systemic restructuring. However, in the short term other digital capabilities overtakeInnovateTech.

Moreover, the analyses reveal similar prioritizes across six agri-food SCs: Grains, Red Meat, Dairy, Horticulture, Seafood, and Wine. These findings suggest that a singular approach to digital technology adoption for SC resilience is undesirable. Instead, a bespoke approach is better as one that is more likely to account for the variance in SC contexts.

5.2. Implications for practice

The findings emphasize the pivotal role of LogisticsTech in ensuring situational awareness and immediate resistance during disruptions in Australian agri-food SCs. Practitioners can leverage advanced logistics systems to monitor transportation conditions, prioritize freshness, and re-route supply to prevent spoilage. For example, during heatwaves or droughts, optimized logistics systems can reallocate resources to underserved or high-demand regions, reducing waste and maintaining SC stability. From a long-term persistence perspective, SecureData emerged as the highest contributor to enhancing resilience. This finding aligned with the growing emphasis on cybersecurity to foster trust among stakeholders as highlighted by Herburger et al. (2024). The importance of this capability was particularly relevant considering recent cyber-attacks on the agri-food sector, such as the 2020 malware attack disrupting wool sales in Australia and New Zealand, and the 2021 cyber-attack on JBS Foods (a leading global food company). These incidents, as reported by the Australian Cyber Security Centre (Rural

Table 6
Examples of disruptions in agri-food SC and digital capabilities for addressing resilience from persistence, adaptation and transformation perspectives.

Agri-food SC	Disruption	Engineering resilience		Socio-ecological resilience		
		Persistence		Adaptation		Transformation
		Short-term (*LogisticsTech*)	Long-term (*SecureData*)	Short-term (*InsightDecision*)	Long-term (*CustomerValue*)	Short & Long-term (*InnovationTech*)
Grains	Severe drought leading to reduction in yields	Re-route limited grain supplies to underserved or high-demand regions to prevent food insecurity and minimize losses.	Integrate data on drought severity, crop yields, and demand to communicate available volumes and timelines, ensuring continuity in trade and market trust.	Predict demand shifts and identify high-value markets for export, optimizing revenues and security during shortages.	Transition to cultivating drought-resilient, gluten-free or high-protein grains tailored to premium markets, meeting evolving consumer preferences.	Establish bio-manufacturing facilities to convert grain husks and residues into nutrient-rich soil additives for drought-affected fields.
Red meat	Geopolitical tensions leading to trade bans and excess	Divert excess meat supplies to domestic markets.	Build trust with new trading partners by traceability and documentation of meat origin.	Identify alternative markets to redirect exports before product spoilage.	Diversify product offerings to create new markets for processed and packaged meats.	Use robotics in creating value-added products, such as pre-marinated or ready-to-eat cuts to reduce dependency on bulk export markets.
Dairy	Prolonged power outages leading to spoilage	Re-rout trucks carrying dairy to nearby urban cold storage facilities powered by backup generators.	Record and monitor cold chain conditions during shipments to meet stringent compliance requirements in international markets.	Predict shifts in processing priorities, converting fresh milk into long-lasting products like cheese or powdered milk.	Diversify product lines by investing in shelf-stable alternatives (e.g., UHT milk, condensed milk).	Establish decentralized cold storage hubs powered by renewable energy.
Seafood	Biohazards or disease outbreaks leading to recalls	Halt distribution of contaminated seafood batches and reallocate safe stock to critical markets	Trace the origin of contamination, identifying affected farms, processing plants, or transport stages to resolve root causes.	Analyse alternative uses for recalled products (non-human use) and set pricing strategies for unaffected batches for revenues.	Implement quality enhancement measures for monitoring seafood processing and farming environments.	Invest in disease-resistant aquaculture species and biosecure farming methods
Horticulture	Heatwaves leading to water scarcity	Optimize water distribution for high-demand crop farms and expedite transportation of harvested crops to nearby urban markets.	Integrate climate and crop health data to monitor water usage and track crop productivity.	Utilize predictive tools to adjust pricing strategies dynamically to offset the revenue loss and avoid buying-related shortages.	Identify heat-tolerant crop varieties and adjust planting schedules based on short-term climate forecasts.	Establish vertical farming systems and climate-controlled greenhouses to ensure production of high-demand crops.
Wine	COVID-19 pandemic disrupting wine demand	Manage the movement and storage of surplus wine effectively and safely, ensuring quality preservation until market conditions improve.	Monitor wine aging processes in storage, ensuring premium products retain their quality for future market recovery.	Repurpose the production line to produce alcohol-based products, such as hand sanitizers, to generate the revenue.	Diversify into fortified wines, low-alcohol alternatives, or organic wines, catering to trends in health-conscious and cost-conscious consumers.	Build e-commerce platforms integrated with blockchain traceability to sell directly to consumers, bypassing traditional trade barriers.

Industries Research and Development Corporation, 2022), underscored the critical role of robust data security measures in maintaining SC resilience in the face of emerging cyber threats.

InsightDecision is shown to be particularly vital for short-term adaptation. this reflects the findings of Bhatti et al. (2024) on the critical role of data-driven decision-making in enhancing SC resilience. The strong influence of InsightDecision indicated that investments in improving this digital capability could yield significant benefits without necessitating extensive changes in other parts of the SC or the implementation of additional digital capabilities. For instance, in the wake of COVID-19 pandemic-induced panic buying in 2020, Australian supermarket chains with advance decision-making technologies were able to quickly identify emerging demand patterns and adjust their operations accordingly (Rahman et al., 2021). For long-term adaptation, CustomerValue is critical in building resilient SCs that maintain product safety and align with evolving consumer needs. The ability to adapt product portfolios, such as by introducing heat-tolerant grains or low-alcohol wines, ensures SCs can evolve alongside shifting market demands while safeguarding product quality. This preference is in line with the findings of Latino et al. (2022) and Shahid et al. (2020), underscoring the critical nature of maintaining product safety and quality, particularly relevant in sectors dealing with perishable goods or bulk commodities.

InnovateTech stands out as the most transformative capability, emphasizing systemic restructuring and reconfiguration of SCs to build future-ready operations. A5 involves systemic restructuring, requiring managers to foster cross-functional collaboration and lead organizational change effectively. It includes decentralized production models, radical technology development mechanisms, and workforce upskilling to align operations with long-term goals. In other words, InnovateTech triggers the National Innovation System (Nelson, 1993; Lundvall, 2007) in the case of Australian agri-food technological ecosystem. Transformation, when built on a foundation of persistence and adaptation, ensures competitiveness. Thus, it is not an isolated process but the culmination of foundational and iterative resilience efforts. Moreover, competitiveness catalyses evolutionary maturity in technological and innovative ecosystems (de Vasconcelos Gomes et al., 2018; Rohrbeck et al., 2009).

Table 6 provides examples of disruptions to agri-food SCs and demonstrates how different digital capabilities can be leveraged to build resilience across persistence, adaptation, and transformation perspectives.

6. Conclusion

This study provides a holistic exploration of digital capabilities and their role in enhancing resilience within Australian agri-food SCs. Through a novel mixed methods approach, the study first develops a taxonomy of five digital capabilities (labelled LogisticsTech, SecureData, ClientValue, InsightDecision, and InnovateTech) and identifies three resilience criteria useful for their evaluation from engineering and socio-ecological perspectives. Second, we identify the priority of adopting each digital capability for agri-food SC resilience across six Australian agri-food SCs—Grains, Red Meat, Dairy, Horticulture, Seafood, and Wine.

Despite its comprehensive analysis, this study has several limitations; It focuses on Australian agri-food SCs, thus, the generalizability of findings to other contexts might be limited. Future research could aim to expand on the findings in this study to other geographical areas or to other sectors outside the agri-food industry, to increase generalizability. The use of expert panels, while valuable for their insights, may introduce potential biases due to the limited number of participants and their specific backgrounds. This might suppress dissenting opinions that could provide valuable alternative perspectives. Future studies might expand the expert panel to include a wider range of stakeholders, including small-scale producers and consumers, to provide a more comprehensive perspective. The network analysis and system dynamics modelling, while powerful tools for understanding interactions and dynamic effects rely heavily on the assumptions and simplifications made during model construction. Employing additional multi-criteria decision-making methods, such as fuzzy TOPSIS, to compare simulation results and validate them with real-world data from specific agri-food SCs to enhance their accuracy and applicability could be considered in future studies. Another valuable follow-up could be conducting case studies in various agri-food sectors to test the practical implementation of the prioritized digital capabilities and assessing their actual impact on SC resilience.

Several additional areas for future research also emerge from this study. First, longitudinal studies of digital capabilities across different agri-food SCs are warranted. Such research could explore how the impact of these digital capabilities evolves over time, particularly focusing on the development of adaptability and transformability, which appear to improve more gradually. Moreover, in-depth comparative studies could help understand why certain digital capabilities were prioritized differently across agri-food sectors, exploring underlying factors such as product characteristics, market dynamics, and regulatory environments. Further research could investigate the cyber resilience strategies specific to agri-food SCs, including the examination of unique vulnerabilities and the development of sector-specific cybersecurity frameworks. Additionally, research exploring the challenges and opportunities in integrating digital capabilities with traditional practices, particularly in sectors with longer production cycles and deeply ingrained traditional methods, could yield important insights for practitioners and policymakers alike.

CRediT authorship contribution statement

Firouzeh Rosa Taghikhah: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Daniel D Prior:** Writing – review & editing, Validation, Investigation, Conceptualization. **Reza Hafezi:** Writing – review & editing, Validation, Software, Methodology. **Derek Baker:** Writing – review & editing, Validation, Supervision, Project administration, Formal analysis, Conceptualization. **Petr Matous:** Conceptualization, Validation, 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 A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.techfore.2025.124191.

Data availability

Data will be made available on request.

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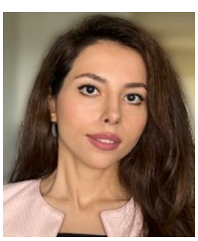

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