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Pragmatic Interoperability for Human–Machine Value Creation in Agri-Food Supply Chains

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Abstract
This study delves into the dynamics of pragmatic interoperability, focusing on the case of a digital ecosystem in India —the eKrishi platform—which combines of industry 4.0 technologies with human-centric principles. Through qualitative analysis, we unveil the motivations shaping system and business-level interoperability alignment. We found that three categories of sustainability metrics—socio-economic, socio-ecological, and eco-efficiency— are driven by diverse pragmatic views. Furthermore, we found that system-level alignment is driven by actors' defensive strategy for compliance and standardization, while business level interoperability is underpinned by actors' offensive strategy for social and economic innovation. The study introduces a 2×2 alignment framework—corporate citizenship, regulatory stewardship, corporate stewardship, and value chain stewardship—offering nuanced insights. By aligning systems and business motives for pragmatic interoperability, we contribute towards theory building on interoperability and provide practical implications for guiding stakeholder alignment in Industry 4.0 initiatives.

Keywords Pragmatic Interoperability · Data Interoperability · Digital Transformation · Digital Platforms · Business Innovation · Digital Supply Chain

1 Introduction

Industry 4.0, with advanced technologies like IoT, blockchain, and precision agriculture, promises to revolutionize agri-food supply chains by enhancing productivity, traceability, and sustainability (Narwane et al., 2022). Central to this transformation is interoperability, enabling seamless interactions among diverse systems and stakeholders. Interoperability spans technical, syntactic, semantic, and pragmatic dimensions (Asuncion and van Sinderen, 2010). While technical interoperability addresses physical and software connectivity, syntactic interoperability ensures data exchange follows a common format. Semantic interoperability maintains the meaning of exchanged information across systems. Pragmatic interoperability, often overlooked, deals with the strategic motives and intentions behind adopting these technologies (Asuncion and van Sinderen, 2010).

1.1 The Problem

In agri-food supply chains, research has emphasized the pivotal role of interoperability in adopting Information and Communication Technologies (ICTs) for precision agriculture (Liu et al., 2021), integrating IoT across supply chains (Narwane et al., 2022), and employing Distributed Ledger Technology (DLT) for traceability and transparency (Pearson et al., 2019). Despite their potential to optimize production and enhance traceability, adoption rates in this sector remain low. Narwane et al. (2022) highlight that only a small percentage of companies have fully integrated these technologies, citing barriers such as high costs, resistance to change, and interoperability issues. Most studies focus on technical

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interoperability, emphasizing hardware and software requirements for seamless data exchange (Glaros et al., 2023). However, this narrow technical focus subsumes measures of pragmatic interoperability into broader technical measures or represents them using technical proxies of pragmatic interoperability. For example, ensuring data format compatibility (technical) is often used as a proxy for actual strategic data use (pragmatic), underplaying the organisational dimensions of pragmatic decision-making that affect business decisions like adopting interoperable tech and sharing data (Brewster et al., 2017).

Syntactic interoperability, involving standardizing data structures for consistent interpretation, also presents challenges. Studies like Renner et al. (1996) showcase the complexities of data heterogeneity, requiring mediation between different data schemas. The debate over strict versus adaptable data standards further complicates the issue (Narwane et al., 2022). Semantic interoperability, ensuring consistent understanding of data meanings, introduces human factors into data interpretation, including behavioural and cultural elements (Khatoon & Ahmed, 2022; Schuurman, 2002; Šestak & Copot, 2023).). While standardized vocabularies and ontologies can facilitate data consistency, they often focus on technical aspects, neglecting the behavioural and organisational motives behind technology adoption (Dooley et al., 2018; Joo et al., 2018).

Pragmatic interoperability, which aligns intended and actual outcomes of data exchange, is critical but underexplored (Asuncion and van Sinderen, 2010). Studies in this area emphasise two core dimensions of pragmatic interoperability, including aligning organisational goals (business-level pragmatic decisions) with technical capabilities and requirements for sharing and using data on interoperable systems like Industry 4.0 (system-level pragmatic interoperability) (Asuncion and van Sinderen, 2010; Muniz et al., 2021). However, the strategic intentions of stakeholders in adopting interoperable technologies are rarely examined (Neiva et al., 2016; Ribeiro et al., 2021).

1.2 Research Gap

Despite extensive literature on interoperability, the unique impact of pragmatic interoperability on technology adoption and strategic decision-making is often conflated with other dimensions. For example, Guo et al. (2024) highlight semantic exchanges in healthcare systems without fully exploring actors' strategic intentions. Their study focuses on the technical standardisation of data to improve patient data quality and accessibility, but it does not delve into why stakeholders might prioritize these improvements, thus missing the pragmatic dimension of strategic intentions. Similarly, Sadeghi et al. (2012) address technical and syntactic interoperability in integrating medical devices within healthcare infrastructures. They outline necessary technical frameworks and data exchange standards but indirectly touch on pragmatic aspects like the strategic importance for improving patient outcomes. This leaves a gap in understanding how stakeholders' strategic intentions impact technology adoption and utilisation. The priorities of these actors may shift over time between compliance and innovation, each requiring different types of interoperability infrastructure and investments (Guo et al., 2024). The agri-food sector presents similar challenges. Burns et al. (2019) and Mouzakitis et al. (2017) underscore the need for SSOT to ensure consistency and MVOT to foster innovation. Yet, the link between strategic data use and the pragmatic motivations of actors remains underexplored.

This conflation of pragmatic interoperability with other dimensions can have significant implications for theory development and practice. For instance, if healthcare actors adopt semantically interoperable system architectures without fully considering both the system-level and business-level pragmatic intentions—like the strategic need for patient-centric care versus compliance—they might find the technology underutilized or misaligned with the primary objectives of system collaborators, leading to wasted resources and missed opportunities (Kannisto et al., 2020; Khatoon & Ahmed, 2022; Ullberg & Johnson, 2017).

1.3 Addressing the Gap

The agri-food sector's struggle to fully realize the potential of Industry 4.0 technologies can be attributed to a lack of strategic data management frameworks. According to DalleMule and Davenport (2017), successful data management requires both a clear strategy and a supportive architecture. Strategic data management can be categorized into "defensive" and "offensive" strategies. Defensive strategies focus on minimizing risks, ensuring regulatory compliance, and maintaining data integrity through a Single Source of Truth (SSOT). This centralized approach ensures consistency and governance, crucial for accurate and reliable data. Conversely, offensive strategies aim to enhance business growth, innovation, and customer satisfaction by employing Multiple Versions of the Truth (MVOT). This approach allows for flexibility, catering to different business needs and facilitating varied data interpretations.

The architecture underpinning these strategies also plays a critical role. The SSOT architecture serves as a centralized, authoritative data repository, ensuring all critical data—such as customer and supplier information—is consistent and standardized across the organization. In contrast, MVOT architectures support business-specific transformation of data into actionable information, tailored to the unique needs of different departments or use cases. Having a dual-architecture approach enables organizations to balance the rigidity needed for compliance and the flexibility required for innovation (Kannisto et al., 2020; Lezoche et al., 2020). However, since technology adoption costs are high and switching costs to change or combine architectures can be prohibitive, actors often make strategic decisions around technology adoption based on pragmatic motives (actual use) irrespective of the value offered (intended use) by such systems (Asuncion and van Sinderen, 2010, Ullberg & Johnson, 2017). In this regard, Davenport and DalleMule argued that simply opting for a 50/50 split between defensive and offensive strategies is rarely effective. Instead, organizations must make strategic trade-offs based on their specific industry, regulatory environment, and business objectives. This approach to data strategy and architecture is vital for leveraging Industry 4.0 technologies effectively but requires an exploration into how actors' pragmatic motives at systems and business levels inform data strategy and ultimately technology adoption implementation and use.

This perspective informs our study, focusing on how pragmatic interoperability impacts the adoption of Industry 4.0 solutions by stakeholders in the agri-food sector with the aim to uncover how actors' pragmatic motives for adopting strategic data frameworks—integrating both SSOT and MVOT architectures—affects technology adoption and utilization. We explore this problem using a case study of the eKrishi platform in India, which offers a unique setting to examine these dynamics. eKrishi is a Cloud-ERP-based agri-food ecosystem that integrates human–machine interfaces and Industry 4.0 technologies, designed around ESG motives (eKrishi, 2019). By assessing actors' choices, the study aims to understand the pragmatic reasons behind their adoption and utilization of different industry 4.0 solutions offered by the platform. To address this aim, the study pursues two research questions:

> **RQ1.** How pragmatic interoperability considerations influence the adoption of SSOT and MVOT strategies in the agri-food sector?
>
> **RQ2.** How these considerations shape the use of offensive and defensive strategies in technology deployment?

Using a qualitative theory-building approach, the study collects data from interviews, field observations, and focus group discussions within the eKrishi ecosystem. This method enables a deep exploration of strategic motives behind interoperability decisions, aligning with business and system-level needs. By focusing on pragmatic interoperability, this study contributes to theoretical discourse on interoperability and system integration for Industry 4.0. It reveals the complexities of aligning business and system levels in stakeholders' strategic motives. Practically, it offers a framework for understanding how business and system-level pragmatic interoperability motives influence the adoption of agro-food data modules. By uncovering these dynamics, the study guides policymakers, technology developers, providers, and food chain actors to align technology adoption strategies with system and business goals.

2 Review

2.1 Industry 4.0 and Supply Chain Interoperability

The agri-food sector is undergoing a significant transformation with the integration of Industry 4.0 technologies, which aim to enhance supply chain efficiency and resilience. Technologies such as the Internet of Things (IoT), big data analytics, and artificial intelligence (AI) promise to optimize production processes, improve traceability, and enhance decision-making. Despite these potential benefits, the adoption of these technologies has been slower than anticipated. Narwane et al. (2022) indicate that only a small percentage of companies have fully integrated Industry 4.0 technologies. The barriers to adoption include high implementation costs, lack of technical expertise, and organizational resistance to change. This review examines these barriers in detail, focusing on the critical aspect of interoperability within the agri-food supply chain.

2.1.1 Technical Interoperability

Technical interoperability is the foundational layer ensuring that different systems can physically and logically connect and communicate. This dimension involves the hardware and software layers that facilitate data transmission between various devices and systems. The digital farmgate sector, as highlighted by Glaros et al. (2023), faces significant technical challenges, including market fragmentation and lack of platform interoperability. These issues impede the seamless data flow necessary for efficient agricultural practices and require substantial investment and detailed planning to overcome. While technical interoperability is crucial, it must be integrated with organizational and cultural shifts to be effective. Brewster et al. (2017) emphasize that cultural changes alongside technological solutions are necessary for successful IoT implementation. Ignoring these broader contexts can lead to suboptimal outcomes where technical solutions are in place, but their potential is not fully realized due to a lack of alignment with organizational practices and goals (Ullberg & Johnson, 2017).

Standards play a vital role in ensuring the quality and interoperability of agricultural data across different regions. Bai (2021) discusses the importance of standards and the role of international and national standards organizations in this process. Bai's study underscores the significant strides made by standards organizations in establishing protocols that facilitate data exchange across borders and platforms. However, the study also highlights a persistent issue: the slow pace of adoption and the inconsistency in implementation across different regions. This inconsistency can create significant barriers to achieving true interoperability. Contrastingly, Lehr (1995) provides a critical perspective on the drive towards standardization. Lehr argues that the ultimate goal of compatibility standardization should not always be interoperability. In some contexts, incomplete standards might be desirable to allow for flexibility and innovation. This perspective highlights the need for balancing standardization and flexibility, as strict adherence to standards can sometimes hinder innovation and adaptability. Lehr's argument is particularly relevant in fast-evolving sectors like agri-food, where overly rigid standards might stifle the innovation necessary for adapting to new technologies and market conditions. Thus, while Bai advocates for a more unified approach, Lehr warns against the potential pitfalls of over-standardization. Case studies illustrate the practical applications of technical interoperability. Sugandh et al. (2024) propose a combined architecture using blockchain, IoT sensors, and smart contracts to mitigate climate disruption in agriculture. Their study underscores the strategic use of such technologies in reducing the costs and penalties of crop losses and increasing productivity through improved climate models and automatic insurance payments. However, like previous studies, they note challenges related to scalability and stakeholder incentives, highlighting the practical complexities of implementing such technologies (Kannisto et al., 2020; Sadeghi et al., 2012).

Blockchain technology has significant potential to transform agriculture by offering a decentralized, transparent, and immutable solution to supply chain challenges. Panwar et al. (2023) conduct a systematic literature review and meta-analysis, highlighting blockchain's positive impact while also noting scalability, legal, and interoperability challenges. They call for future studies on the role of stakeholder involvement and clear legislation as key factors in blockchain implementation within agricultural contexts. Similarly, Leong et al. (2023) discuss the transformative potential of Artificial Intelligence of Things (AIoT) in agriculture, noting benefits like increased efficiency, improved decision-making, and enhanced sustainability. They also identify challenges such as data quality, connectivity, and user adoption, suggesting future research directions that include promoting interoperability and standards.

2.1.2 Syntactic Interoperability

Syntactic interoperability involves the structure and format of data, ensuring that data exchanged between systems adheres to a common standard for interpretation across different platforms. Kamilaris et al. (2017) emphasize the importance of standardized data structures to facilitate seamless communication across various systems within the agri-food supply chain. Standardization is essential for enabling systems to understand and process exchanged data correctly, thus enhancing operational efficiency. However, there is an ongoing debate about the balance between standardization and flexibility. While some argue that strict standardization is necessary to ensure compatibility and interoperability, others contend that flexibility is equally important. Narwane et al. (2022) highlight the need for flexibility to accommodate different environmental and organizational contexts in which IoT technologies are deployed. This suggests that syntactic solutions must be adaptable, allowing for variations in data formats and structures to meet specific needs without compromising interoperability. Renner et al. (1996) illustrate the complexities of data heterogeneity, demonstrating how different data schemas require mediation to achieve interoperability. Their work underscores the need for both standardization and flexible mediation to address structural and naming differences in data systems. This aligns with the broader literature on syntactic interoperability, which revolves around concepts of data standardization and structural compatibility, focusing on managing the dichotomy between standardization and flexibility in technology deployment.

2.1.3 Semantic Interoperability

Semantic interoperability ensures that the meaning of exchanged data is preserved and understood consistently across different systems. This dimension introduces the role of human actors, as semantic interpretation often involves behavioral, cultural, and contextual elements (Rejeb et al., 2022). Schuurman (2002) discusses the challenges of semantic standardization in sharing geographic information across multiple platforms, arguing that current interoperability approaches often exceed the sophistication and funding available to local government agencies, necessitating flexible and interim solutions. Šestak and Copot (2023) explored semantic interoperability through the lens of Agricultural Data Spaces (ADS), identifying significant challenges such as mistrust and unclear data ownership. These issues, if not addressed through robust semantic frameworks, can severely impact effective data sharing. Their work proposes design principles for ADS that underscore the importance of ensuring data retains its intended meaning and utility as it moves across different systems. Standardized vocabularies are crucial for semantic interoperability. Joo et al. (2018) introduced the

Crop Vocabulary (CVO) to address interoperability issues related to crop names by integrating vocabularies from multiple government agencies. Their approach demonstrates the value of standardized vocabularies for ensuring interoperability and machine-readability in agriculture. Similarly, Almadani and Mostafa (2021) developed a multimodal communication model using DDS middleware to enable real-time interoperability between multi-vendor agricultural systems. This approach underscores the practical significance of semantic frameworks in facilitating seamless data exchange and interpretation. The interplay between machine-generated semantics and human understanding highlights the pragmatic aspect of interoperability, often overlooked in the literature. For example, the FoodOn platform, as presented by Dooley et al. (2018), is a comprehensive food ontology aimed at enhancing global food traceability and data integration by developing a standardized vocabulary and logical relationships. Their approach emphasizes the importance of semantic standardization in ensuring data consistency and traceability in the agri-food sector.

While studies like those by Poppe et al. (2013) argue that semantic interoperability is vital for technical integration, they also stress that it must be coupled with pragmatic considerations to address real-world challenges in data integration and usage. In the agri-food sector, interpreting data related to crop conditions, market trends, and supply chain logistics involves both machine-generated insights and human decision-making processes. The semantic layer must accommodate the nuanced understanding that humans bring to these contexts, which often includes behavioral and cultural factors. Narwane et al. (2022) underscore the importance of incorporating these human elements into semantic interoperability frameworks to ensure that data is not only technically accurate but also contextually relevant and actionable. This highlights the need for a holistic approach that integrates technical, syntactic, and semantic interoperability to fully realize the benefits of digital technologies in the agri-food sector (Ullberg & Johnson, 2017).

2.1.4 Pragmatic Interoperability

Pragmatic interoperability has emerged as a pivotal concept in the broader discourse of interoperability, transcending the traditional focus on syntactic and semantic dimensions to emphasize the practical use and intended outcomes of data exchange. Asuncion and van Sinderen, (2010) defined pragmatic interoperability as the compatibility between the intended and actual effects of message exchanges in inter-organizational settings. They argue that achieving effective interoperability extends beyond the technical and semantic layers, requiring a focus on the practical use of data and the actions it precipitates. The operationalization of pragmatic interoperability involves evaluating how well data exchange supports intended business outcomes and user actions (Kannisto et al., 2020). Key measures include intentional alignment (the degree to which exchanged data aligns with organizational goals and intentions), contextual relevance (the extent to which data is meaningful and useful in specific organizational contexts), process integration (how effectively data exchange integrates with and supports business processes), and outcome effectiveness (the impact of data exchange on achieving desired business outcomes) (Ullberg & Johnson, 2017).

Empirical studies such as those by Neiva et al. (2016) introduce models that integrate business processes with technical solutions to support collaboration in distributed environments. Their study on collaborative business networks in Brazil found that aligning business processes with technical solutions was crucial for effective collaboration. By integrating technical capabilities with business needs, they demonstrated how pragmatic interoperability could improve operational efficiency and stakeholder satisfaction. Ribeiro et al. (2021) extend the discourse of pragmatic interoperability to cloud computing by exploring how enhanced MIDAS middleware facilitates pragmatic interoperability by reducing overhead and improving dynamic information exchange. Their study in the context of Brazilian SMEs showed that improved middleware significantly enhanced operational efficiency and data sharing.

Muniz et al. (2021) explored how to improve developer collaboration within IoT contexts by proposing a service that supports pragmatic interoperability through inferences and similarity calculations. Their study on IoT ecosystems found that pragmatic interoperability could significantly enhance collaboration efficiency by aligning technical frameworks with the practical needs of developers. This highlights how monitoring technical measures of developer feedback can facilitate collaboration efficiency in software development and improve interoperability among heterogeneous systems.

Healthcare provides a unique and complex environment for exploring pragmatic interoperability. Weber and Kuziemsky (2019) address interoperability within healthcare workflows by proposing workflow patterns to tackle common issues such as patient referrals and data sharing. They measure the effectiveness of these patterns through case studies and workflow simulations, focusing on metrics like process efficiency and error reduction. Their study emphasizes the need for adaptable frameworks that can evolve with healthcare processes, highlighting the dynamic interaction between technology and human actors. In military healthcare settings, Hall et al. (2024) examined medical interoperability under resource constraints. They used scenario-based assessments to measure system performance, focusing on metrics like response time and accuracy. Their theoretical exploration centered on how assured and pragmatic interoperability impacted operational performance in such settings, where the former is high-cost and resource-intensive, and the latter is more adaptable and feasible in resource-limited environments.

Giaffreda et al. (2016) further exemplify the empirical application of pragmatic interoperability in the eHealth domain. Their study focuses on integrating heterogeneous wearable and positioning technologies to monitor elderly patients remotely. The empirical results demonstrate how pragmatic design choices can enhance interoperability, yet the study primarily addresses technical solutions and lacks a deeper exploration of strategic implications. These studies underscore the necessity of socio-technical alignment but also reveal a gap in strategic understanding and implementation. While these studies support and illustrate the practical benefits of pragmatic interoperability in various settings, they do not fully explored how strategic considerations of actors about the expected and actual use of data (e.g., for compliance or operational efficiency) might impact interoperability considerations, focusing primarily on demonstrating the technical benefits and challenges (Hardt et al., 2017).

In the industrial and agricultural domains, Horsch et al. (2020) and Baker et al. (2019) provide critical insights into pragmatic interoperability. Horsch et al. (2020) discuss the importance of community-governed agreements to complement syntactic and semantic interoperability in materials modeling. They advocate for community-driven standardization of ontologies, using case studies and simulations to demonstrate how community-driven standardization enhances interoperability. However, they do not explore the interoperability motives of the parties to such community-governed agreements, which is an important consideration in adopting and using semantic and syntactic standards, given the power, resource, and knowledge disparities among key actors. Baker et al. (2019) introduce the Global Agricultural Concept Space (GACS), a semantic framework aimed at enhancing data interoperability in food technology research. Their empirical work involved mapping frequently used concepts from various thesauri to create a unified vocabulary. The study measured the framework's effectiveness through metrics like term coverage and user adoption rates. While such studies provide valuable technical solutions to the issue of pragmatic interoperability, they often overlook how stakeholders' strategic intentions impact the adoption and use of semantic and syntactic standards.

From the diverse literature on pragmatic interoperability, it is evident that the concept is well-defined as the alignment between intended and actual use of data, with a strong emphasis on context and practical outcomes (Hardt et al., 2017). Empirically, studies have provided valuable technical solutions and frameworks, demonstrating the importance of socio-technical alignment and dynamic adaptability. However, many focus predominantly on technical and processual aspects, with limited attention to the broader strategic drivers and barriers influencing organizational decisions.

2.2 Theory

2.2.1 Data Strategy and Interoperability

DalleMule and Davenport (2017) articulate two distinct data strategies: offensive and defensive. Offensive strategies are geared towards leveraging data for business growth, innovation, and competitive advantage. This approach emphasizes data analytics, customer insights, and market responsiveness to drive revenue and enhance operational efficiency. Conversely, defensive strategies prioritize data security, compliance, risk management, and data integrity, ensuring that data practices meet regulatory requirements and protect against breaches and other threats. These strategies align with two prominent data architectures: Single Source of Truth (SSOT) and Multiple Versions of the Truth (MVOT).

SSOT is designed to provide a consistent and accurate data source across an organization, supporting defensive strategies by ensuring data integrity, reducing errors, and facilitating compliance. This architecture simplifies data governance and enhances control, which is critical for defensive data management (Dallemule & Davenport 2017). SSOT emphasizes a centralized data repository to ensure data integrity and uniformity, as highlighted by Belkadi et al. (2024) in their work on soil data management in the Maghreb region. This approach facilitates standardized data governance and integration with technologies such as blockchain, which enhances traceability and security (de la Parte et al., 2024). In theory, SSOT supports robust decision-making processes by ensuring that all stakeholders access consistent and accurate data, reducing the risk of discrepancies that can arise from siloed data systems (Rejeb et al., 2022). However, the practical implementation of SSOT in the dynamic agri-food environment reveals several challenges. The rigidity required to maintain a single, centralized source of truth can be cumbersome, particularly in diverse agricultural settings where local variations are significant. For instance, Bouadi et al. (2017) illustrate the difficulties of applying uniform data models across varied agricultural contexts, which can hinder the responsiveness to local conditions and practices. Moreover, the high infrastructure costs and complexity associated with SSOT can be prohibitive, especially for smaller farms or regions with limited technological capabilities (Bimonte et al., 2021; Hardt et al., 2017). These constraints highlight the need for flexibility and adaptability in data management strategies, which SSOT alone may not adequately provide.

In contrast, MVOT architecture supports offensive strategies by enabling different departments or functions within an organization to use tailored data sets that suit their specific needs. MVOT allows for flexibility and agility, enabling quicker responses to market changes and customer demands. MVOT allows for a context-sensitive approach to data management, as demonstrated by Bimonte et al. (2021) in their work on environmental data warehouses for fertilizer pesticide management. By integrating data from diverse sources, they proposed a MVOT architecture that supports complex, multi-faceted analyses that can better address the specific needs and conditions of different agricultural settings. This flexibility is purported to enhance the resilience and adaptability of agricultural systems, particularly in response to changing environmental conditions and technological advancements. However, MVOT is not without its challenges. The primary issue is the potential for data inconsistency and fragmentation, which can undermine the reliability of decision support systems. Additionally, the complexity and cost of integrating and reconciling data from diverse sources can be significant, posing challenges for effective implementation (Hardt et al., 2017; Weber & Kuziemsky, 2019). Furthermore, MVOT architectures can complicate data governance and increase the risk of inconsistencies, making it less aligned with purely defensive strategies.

2.3 Research Gaps and Study Positioning

A critical comparison of SSOT and MVOT reveals distinct advantages and disadvantages depending on the context. SSOT excels in scenarios requiring high data integrity and centralized control, while MVOT offers greater flexibility and adaptability to local conditions. While SSOT can streamline data management and enhance interoperability, it may also stifle innovation and responsiveness to local needs (Bimonte et al., 2021). This dichotomy suggests that neither approach is universally superior; instead, the choice between SSOT and MVOT should be informed by the specific requirements and constraints of the context in which they are implemented. Therefore, the alignment between data architecture (SSOT and MVOT) and data strategy (offensive and defensive) requires an exploration of both technical and strategic dimensions. Existing studies often emphasize on the advantages, challenges, and solutions provided by SSOT and MVOT architectures independently or in hybrid implementations, there is a notable gap in understanding how these architectures align with offensive and defensive data strategies at both the system and business levels (de la Parte et al., 2024; Ullberg & Johnson, 2017; Weber & Kuziemsky, 2019). The first gap we explore is that there is limited research on how the architectural choices (SSOT and MVOT) intersect with strategic objectives (offensive and defensive). While digital architectures have been explored in many studies, their alignment with actors defensive or offensive strategic motives is overlooked in most studies. DalleMule and Davenport (2017) argued that the most successful organizations are those that are capable of a blended strategy where SSOT and MVOT are used defensively and offensively, depending on several business and system considerations such as the industry norms, size of actors, scope of operations and the strategic business needs of stakeholders. DalleMule and Davenport (2017) conceded that the solution to this trade-off is not as simple as settling for a 50–50 split between offensive and defensive strategies, as this could be prohibitive considering that the underpinning SSOT and MVOT architectures are different.

Secondly, some empirical evidence from various studies supports the potential benefits of a hybrid approach that combines elements of both SSOT and MVOT. De la Parte et al. (2024) advocate for a distributed data management framework that integrates centralized and decentralized elements to maximize interoperability and adaptability. Their use of blockchain technology demonstrates how a hybrid approach can enhance data security and integrity while maintaining flexibility. Studies such as those by Bouadi et al. (2017) and Bimonte et al. (2021) also highlights the practical benefits of integrating SSOT and MVOT elements. These studies show that while a pure SSOT or MVOT approach may be suboptimal, a combined strategy can leverage the strengths of both to address the complex and dynamic nature of the agri-food sector.

Furthermore, pragmatic interoperability varies significantly from actor to actor. In complex settings, the perceptions and experiences of stakeholders are crucial yet often overlooked. The current literature tends to draw conclusions about technological, syntactic, and semantic interoperability without adequately incorporating how stakeholders' pragmatic interoperability considerations influence the ways in which they view Industry 4.0 offerings. For instance, studies such as Bouadi et al. (2017) and Bimonte et al. (2021) reviewed earlier illustrate the challenges of applying uniform data models across varied agricultural contexts, highlighting the need for flexibility and adaptability. However, they do not fully analyze the intersection of SSOT and MVOT strategies. To illustrate the point further, studies on healthcare interoperability often favour a single source of truth architecture to ensure a data defensive data strategy for integrity and uniformity across patient records, as highlighted by Giaffreda et al. (2016). Conversely, in retail, multiple versions of truth are more prevalent to accommodate the diverse data needs across various supply chains and customer interactions. This distinction is also evident in how environmental, social, and governance (ESG) metrics are managed. Certain ESG metrics, like compliance and regulatory reporting, tend to align more with single source of truth strategies, while others, such as market-based environmental impact assessments, may benefit from multiple versions of truth to reflect the diverse data inputs and interpretations required. Moreover, studies like those by Panwar

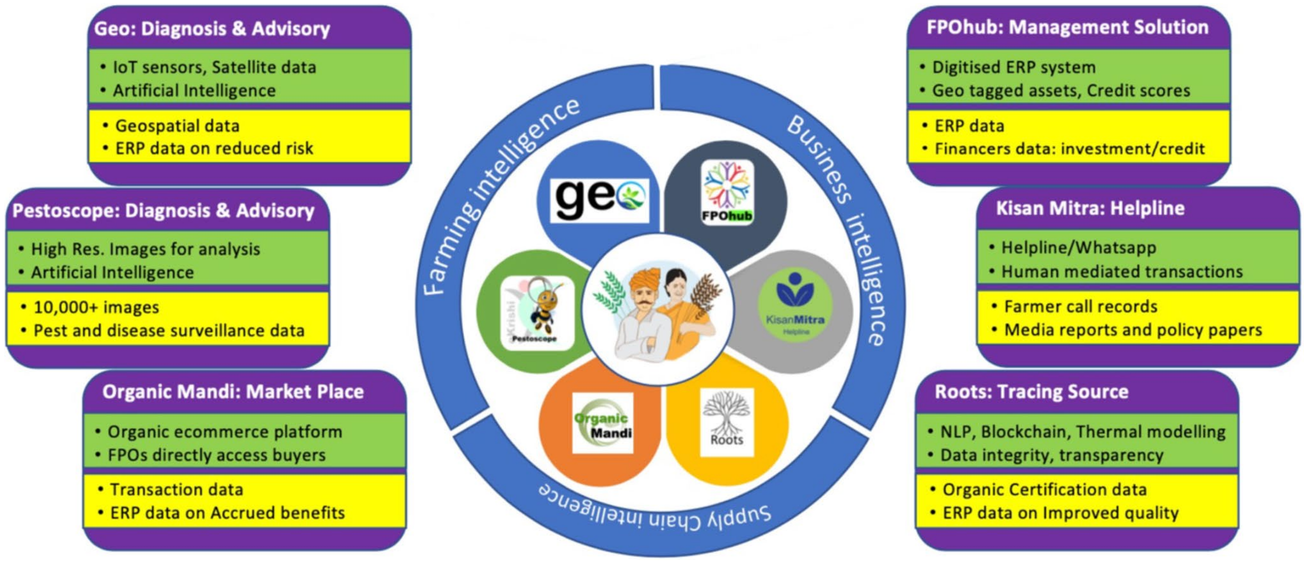

Fig. 1 eKrishi: Integrated Platform

et al. (2023) on blockchain in agriculture demonstrate how the pragmatic reasons for adopting technologies can be influenced by the need for transparency and traceability, which align differently with SSOT or MVOT strategies. Similarly, Renner et al. (1996) illustrate the complexities of data heterogeneity, showing how pragmatic considerations necessitate mediation between different data schemas, further highlighting the need for adaptable and flexible data strategies. Our study addresses these gaps by adopting a pragmatic interoperability framework that allows us to examine the system-level and business-level dimensions of pragmatic interoperability. This approach enables us to explore how the juxtaposition of these pragmatic interoperability objectives or motives affects actors' adoption of SSOT or MVOT, as well as their use of offensive or defensive strategies.

Summarising, our review shows that interoperability studies often conflate pragmatic interoperability with technical, semantic, or syntactic interoperability, which are primarily process-oriented facets. This conflation obscures the unique impact of pragmatic interoperability on technology adoption and vice versa. Asuncion and van Sinderen, (2010) highlighted the need for studies to evaluate how advanced technologies for data exchange support or undermine the intended and actual business outcomes and user actions, which is a key aspect of pragmatic interoperability that remains underexplored. This study aims to disentangle these relationships, providing a clearer picture of how pragmatic interoperability specifically affects the adoption of Industry 4.0 technologies.

3 Methodology

3.1 Selection of the E-Krishi Platform Case

The E-Krishi platform was selected for this study due to its comprehensive integration of technological, semantic, and syntactic components essential for examining pragmatic interoperability. E-Krishi enhances agricultural productivity and market access through advanced technologies such as data analytics, advisory services, and transaction facilitation. Its multifaceted nature provides a diverse user base, including smallholder farmers, large-scale producers, agronomists, and technology providers, offering varied perspectives on platform adoption and use (Heritage & Clayman, 2010). The platform's deployment across different settings—from individual farms to collective processing units—allowed for observation and analysis of conversations in varied operational contexts (see Fig. 1). The CEO of E-Krishi, with assistance from the Society for Elimination of Rural Poverty (SERP) and other organisations, facilitated access to a wide range of stakeholders, ensuring diverse perspectives were captured.

3.2 Data Collection

Data collection began with interviews with the founder and CEO of CSA in Hyderabad, India, to discuss the study's scope and objectives. Respondents were identified through collaborative efforts between the authors and CSA leadership, leveraging their insights to gather additional perspectives on actors' system and business-level pragmatic interoperability considerations. A 3-day participatory workshop involved twenty public and private stakeholders with access to the eKrishi platform, including farmers' organizations, practitioners, technology providers, banks, NGOs, certification bodies, policymakers, consumers, and technical domain experts from the UK Science and Technology Facilities Council (STFC) (Piekkari & Welch, 2018). The workshops generated valuable insights into stakeholders' perceptions, focusing on the minimum viable set of indicators facilitating pragmatic alignment for interoperability and Industry 4.0 technologies. Subsequently, 20 in-depth interviews were conducted with field actors, each lasting 45 min to 1 h. Respondents were strategically chosen based on their qualifications, roles, and relevance to the research questions.

Participants were purposefully sampled to explore the agri-food landscape comprehensively. Farmers ranged from small-scale conventional to organic practitioners, offering insights into varied practices. Farmer Producer Organization (FPO)-owned Collection Centres provided perspectives from organized entities, reflecting collective farming approaches. Collection Centres and Aggregators, both private and FPO-associated, represented different distribution models, capturing nuances in interoperability needs. CSA participants contributed strategic insights, while Society for Elimination of Rural Poverty (SERP) members added operational and financial perspectives. Engagement with online retailers, including CEOs and Procurement Managers, provided digital platform insights. With experiences ranging from 7 to over 30 years, participants ensured a holistic understanding of pragmatic interoperability in eKrishi, embracing the diverse facets of India's agri-food operations. Demographic details are captured in Table 1. The first round of interviews was conducted in 2019 during a 3-month period of interdisciplinary fieldwork for Project TRANSSITioN. Follow-up interviews were conducted as necessary (Piekkari & Welch, 2018). A validation workshop was run in 2022 with eighteen stakeholders who were a mix of interviewees and the first workshop participants.

To gather structured data, six leading questions were framed: (1) How do you currently use the E-Krishi platform? (2) What specific challenges have you faced with the platform? (3) How does the platform's data analytics feature impact your decision-making? (4) Which modules of the platform do you find most beneficial? (5) How do the advisory services provided by the platform support your agricultural practices? (6) In what ways do you think the platform could be improved? These questions aimed to elicit detailed responses reflecting pragmatic interoperability concerns, aligning with the theoretical basis of understanding Industry 4.0 applications in the agri-food sector (Bertolini et al., 2019). The questions aimed to uncover the perceived value and practical applications of the platform's modules, facilitating a comprehensive understanding of how different functionalities meet strategic objectives.

3.3 Data Analysis and Coding Approach

Conversation Analysis (CA) was chosen as the primary analytical approach due to its effectiveness in examining detailed, sequential interactions. CA allows for an in-depth understanding of how participants construct meaning and negotiate value through talk. Given the fragmented nature of the agri-food chain and varying technological competencies among actors, analysing the fine-grained details of their conversations was essential to uncover underlying pragmatic motivations for using different modules of the E-Krishi platform (Sacks et al., 1974). CA focuses on aspects like turn-taking, adjacency pairs, repair mechanisms, and sequential organization. Turn-taking examines how participants manage conversation flow, including how turns are initiated, maintained, and completed (Sacks et al., 1974). This is crucial for understanding how actors assert control, distribute speaking opportunities, and establish roles within conversations about the platform. Adjacency pairs involve paired actions such as questions and answers, fundamental to conversational structure (Schegloff, 2007). These pairs help identify how actors respond to inquiries, provide feedback, and build shared understanding. Repair mechanisms analyse how participants address and correct misunderstandings or conversational breakdowns, offering insights into strategies used to maintain coherence and mutual comprehension. Sequential organization examines the order and structure of conversational elements, understanding how interactions build sequentially (Schegloff, 2007). This helps uncover patterns of how actors negotiate meaning and make decisions over time.

Thematic analysis was integrated with CA to identify broader patterns and themes within the data. This approach allowed for structured analysis while maintaining the richness of interactional contexts (Heritage & Clayman, 2010). Initial coding was based on recurrent themes observed in the data, such as technological requirements, data needs, and perceived values. The coding scheme was systematically applied to the transcripts, tagging relevant sections of the conversation. The coded data were then analyzed to identify overarching themes and insights, synthesizing findings to draw broader conclusions about participants' motivations and expectations (Hindmarsh & Llewellyn, 2018).

3.3.1 Archival Data and Triangulation

Archival data from E-Krishi's records, reports from SERP, and other documentation were analyzed to triangulate findings. This archival data provided a historical perspective on the platform's development, user engagement patterns, and the impact of different modules over time. Triangulation

Table 1 Summary of Interviews and participants

Interview respondents' details and associated respondent codes				
Individual/ Organisation	Description of Study Participant	Respond-ent code	Interview length (mins)	Interviewers
Farmer 1	Small-scale vegetable farmer practising conventional farming (mostly growing tomatoes), supplying to supplying to private collection centre	A1	45	1
Farmer 2	Small-scale vegetable farmer practising organic farming for more than 10 years (growing a mix of vegetables on small plots), supplying to private collection centre	A2	55	2
Farmer 3	Small-scale vegetable farmer practising conventional farming for more than 25 years (growing a mix of vegetables on small plots), supplying to Farmer Producer Organiser (FPO) owned Collection Centre (CC)	A3	59	2
Farmer 4	Small-scale vegetable farmer practising Organic farming for more than 15 years (mostly growing tomatoes), supplying to FPO-CC	A4	58	2
Farmer 5	Small-scale vegetable farmer recently converted to practising Organic farming for 2 years (mostly growing leafy greens) supplying to FPO-CC	A5	47	1
Collection centre 1 (Facility Director)	FPO-owned Village Level Procurement Centre (FPO-CC) for specialist retailers and other distribution centres	B1	46	2
Collection centre 2 (Facility Director)	Privately owned Collection Centre by different organised retailers	B2	45	2
Aggregator 1 (System Administrat or)	Privately owned Distribution Centre by different organised retailers	C1	47	2
Aggregator 2 (System Administrator)	A hybrid CC-DC services for connecting food producers directly to retailers, restaurants, and service providers, through technology and digitisation	C2	56	2
Aggregator 3 (System Administrator)	Wholly owned subsidiary of a national development board that is into manufacturing, marketing, and selling dairy products, edible oil, fruits and vegetables	C3	60	3
CSA (NGO)	Co-Director with more than 35 years of experience in providing agriculture extension services and regarded as one of the top policy advisors to the national and regional governments on agri extension services	D	60	3
CSA (NGO)	Head of knowledge management in agronomic practices with over 15 years of experience	E	45	1
CSA (NGO)	Senior Scientist in Soil Science with more than 12 years of experience	F	46	1
CSA (NGO)	Business and financial analyst with more than 10 years of experience	G	50	2
CSA (NGO)	Environmental Analyst with more than 7 years of experience	H	47	1
CSA (NGO)	IT Manager with more than 8 years of experience in ERP system	I	59	3
Society for Elimination of Rural Poverty (SERP)	Chief Operating Officer (COO) for Agriculture Unit with more than 15 years of experience	J1	58	3
Society for Elimination of Rural Poverty (SERP)	Director for finance and IT Unit with more than 10 years of experience	J2	56	2

Table 1 (continued)

Interview respondents' details and associated respondent codes

Individual/ Organisation	Description of Study Participant	Respond-ent code	Interview length (mins)	Interviewers
Regional Online Retailer 1	Director/ CEO of Specialist Retailer Organic producer company wholly owned by organic producers with extensive consumer-producer network for procurement and supply, having more than 30 years of experience in retailing	K1	60	3
National Online Retailer 2	Procurement Manager with 8 years of experience at a National E-tailer	K2	57	2
Total		20	1056	

through these multiple data sources ensured the robustness of our findings and provided a comprehensive understanding of the platform's use and perceived value (Heritage & Clayman, 2010).

3.3.2 Transcription and Coding

Despite most respondents' proficiency in English, an interpreter was utilized to translate interview responses given in Telugu where needed. Researchers transcribed field notes, case-based memos, and interview recordings to capture respondents' experiential narratives and pragmatic interpretations of value. Given the study's focus on actors' pragmatic interpretations of Industry 4.0 technologies, data, and modules at the system and business levels, CA was employed. CA investigates how sequences of talk are related and how speaker identities are enacted in those sequences. Drawing on systemic functional linguistics as an analytical framework, CA deduces meaning from conversations by analysing the structure and order of the text to understand the semantic meaning implied by interviewees in their social context (Gubrium & Holstein, 2008). The coding process identified keywords linked to different extant indicators of resilience and sustainability to understand how actors prioritised each of the eKrishi modules.

Our analysis allowed us to identify both business-level and system-level pragmatic interoperability motives captured through actors' conversations about the eKrishi platform modules. We found three primary business-level motives: socio-economic (e.g., enhanced market access via the FPO Hub and Organic Mandi), socio-ecological (e.g., sustainable practices through the Pestoscope), and eco-efficiency (e.g., resource optimization using Geo and Roots modules). Conversely, system-level motives were focused on technical integration, data harmonization, and broad technological compatibility. This analysis revealed that while system motives aimed at efficient data integration, business motives emphasized immediate, practical benefits for stakeholders, such as financial gains and sustainability practices. These contrasting yet complementary motives highlight the complex interplay between different levels of pragmatic interoperability, providing a comprehensive understanding of how stakeholders derive value from the platform.

To address our second research question, responses and conversations were coded by stakeholder groups using a 2 × 2 framework comprising the dimensions of system-level and business-level pragmatic interoperability motives (see Table 2). For system-level motives, we synthesized actors' considerations on platform integration, data harmonization, and broad technological compatibility. Business-level motives encompassed individual or organizational goals, such as enhancing productivity, reducing costs, improving decision-making, and achieving sustainability targets. Using this framework, we categorized eKrishi stakeholders into four distinct categories:

1. High System-Level, High Business-Level Pragmatic Interoperability: Stakeholders in this category prioritize both extensive technological integration and significant business benefits. For example, a large agribusiness might invest in comprehensive data analytics modules that provide real-time insights for decision-making and operational efficiency.
2. High System-Level, Low Business-Level Pragmatic Interoperability: These stakeholders emphasize robust system integration but have limited immediate business gains. For instance, a regulatory body might focus on ensuring data standardization across platforms without direct financial benefits.
3. Low System-Level, High Business-Level Pragmatic Interoperability: Stakeholders here prioritize business benefits over system integration. A small-scale farmer, for example, might adopt certain modules that directly

Table 2 Thematic coding scheme

Analytical Theme	Alignment	Second-Order codes	First-Order codes	Description
Corporate Citizenship	Low Business-Level	Limited Social Engagement and Governance for Interoperability (LSE)	Minimal Business Community Involvement (MBCI)	Demonstrates minimal business community involvement, with limited interaction or contribution to social initiatives
			Business Social Apathy (BSA)	Displays a lack of interest or concern for social issues from a business perspective, indicating low alignment with corporate citizenship
	Low System-Level	Limited Environmental Initiatives (LEI)	Limited Eco-Friendly Business Practices (LEF)	Lacks significant environmental initiatives and shows minimal implementation of eco-friendly practices from a business standpoint
			Business Environmental Disregard (BED)	Demonstrates a disregard for environmental concerns, showcasing low alignment with corporate citizenship from a business-level perspective
Corporate Stewardship	High Business-Level	Strategic Sustainability (SS)	Business Global Sustainability Adherence (BGSA)	Adheres to global sustainability practices, strategically integrating sustainability into business goals
Corporate Stewardship			Business Environmental Leadership (BEL)	Takes a leadership role in environmental initiatives from a business perspective, showcasing commitment to strategic sustainability
Corporate Stewardship	Low System-Level	Limited Systems Innovations for Sustainability (IFS)	Business Sustainable Innovation Practices (BSIP)	Limited emphasis on sustainable innovation practices, integrating innovative solutions for long-term sustainability
Corporate Stewardship			Business Forward-Thinking Solutions (BFTS)	limited forward-thinking solutions, aligning innovation efforts with sustainability goals from a systems capability perspective
Regulatory Stewardship	Low Business-Level	Low Business Compliance (BC)	Business Transparent Regulatory Practices (BTRP)	Practices at the business level less transparent, impacting openness and clarity in supply chain business compliance efforts
			Business Regulatory Rigor (BRR)	Limited traceability of regulatory compliance at the business level for standardising value chain approach to adherence
	High System-Level	Risk-Aware Regulatory Approach (RARA)	Regulatory Compliance Risk Mitigation (BCRM)	Proactively mitigates compliance risks at the business level, showcasing a risk-aware approach to regulatory practices
			Business Proactive Regulatory Strategy (BPRS)	Adopts a proactive strategy for regulatory compliance at the business level, emphasizing a forward-thinking approach
Value Chain Stewardship	High Business-Level	Integrated Supply Chain (ISC)	Business Customer-Centric Supply Chain (BCCSC)	Prioritizes a customer-centric supply chain from a business perspective, integrating customer needs into the core of the value chain
Value Chain Stewardship			Business Seamless Value Chain Integration (BSVCI)	Achieves seamless integration across the value chain at the business level, optimizing processes for efficiency and collaboration
Value Chain Stewardship	High System-Level	Quality Assurance Excellence (QAE)	Traceability for Business Efficient Product Quality (BEPQ)	Ensures efficient traceability for product quality through rigorous quality assurance at the business level, aligning with high system-level standards
Value Chain Stewardship			Transparency for Business Rigorous Quality Control (BRQC)	Maintains rigorous and transparent quality control processes at the business level, emphasizing high standards in quality assurance practices

improve productivity and reduce costs without fully integrating them into a broader technological framework.

4. Low System-Level, Low Business-Level Pragmatic Interoperability: These stakeholders show minimal engagement with both technological integration and business improvement. This could include traditional farmers who rely on legacy systems and are skeptical of new technologies, focusing instead on conventional methods with limited interoperability.

3.3.3 Validity and Reliability

To ensure the validity and reliability of our findings, we adhered to the principles of trustworthiness as outlined by Lincoln and Guba (1985). This involved maintaining a detailed audit trail of all data collection and analysis processes, ensuring transparency and reproducibility (see Table 3). Member checking was also employed, where preliminary findings were shared with participants for validation and feedback. Triangulation was achieved through the use of multiple data sources, including primary interviews, focus groups, informal conversations, and archival data, which provided a well-rounded perspective on the research questions. Triangulation was a critical component in synthesizing our findings to address our second research question. By combining data from primary and archival sources, we were able to cross-verify and validate the themes and patterns identified through CA and thematic analysis. This comprehensive approach allowed us to develop a 2 × 2 framework of system-level and business-level pragmatic interoperability motives. This framework mapped stakeholders into categories based on their pragmatic interoperability motives and strategic intentions for using interoperable technology and data. It helped us understand how actors align system-level and business-level pragmatic interoperability motives around different technological and data use strategies.

By employing this systematic approach, we uncover the nuanced ways in which actors within the eKrishi ecosystem align their system and business-level pragmatic interoperability considerations with the broader goals of sustainability and resilience. This methodological framework allowed for a comprehensive understanding of how different actors prioritize and value the various technological modules and their contributions to an integrated, interoperable agri-food supply chain.

4 Findings

4.1 Pragmatic Interoperability Data Requirements for Industry 4.0 in eKrishi

Table 4 shows a summary of our mapping of *eKrishi*' modules against industry 4.0 metrics of sustainability and resilience indicators drawing on the literature and actors views on the relevant 4.0 technologies in smallholder food supply chains in India. Actors mapped each *eKrishi* module against several indicators of sustainability and resilience, highlighting that actors' pragmatic views on the system and business-level data requirements for each module and the required data categories, metrics and indicators. The number of metrics associated to each module is shown by (✓) and the modules are categorised as providing **socio-economic value** (FPOHub, Organic Mandi modules), **socio-ecological value** *(Pestoscope module*) and **eco-efficiency** *(Geo and Roots modules).*

4.2 Pragmatic interoperability Value Streams for Industry 4.0 technologies in eKrishi

4.2.1 Socio-ecological Interoperability Value

5 Pestoscope (Pest and disease surveillance)

One of the most important aspects that could impact the economic, social, and environmental aspects of farming performance, is effective pest and disease control for farms. Respondents from Case A acknowledged that not having access to quality and real-time data, leaves them vulnerable to sudden disruption and this could impact their revenue and the substantial indirect economic impacts pests could have on their equipment, machinery, and their properties:

> *If a particular damaged crop is left untreated it could infect the whole batch. This is tricky since with untrained eyes it is difficult to efficiently recognise and identify a particular disease before it spreads. When it spreads it is too late to intervene to save a seasonal production batch*

Lack of support with pest and disease monitoring-control and the resulting financial impact could force marginal farmers to tap into their savings for emergencies (or investment in other crops/lands). This was reflected by the respondent

Table 3 Criteria for trustworthiness of study and findings

Trustworthiness Criteria	Approach	Result
Credibility	Engaged in seven-year field studies with diverse stakeholders, including multi-stakeholder consultations. Modified alignment criteria post-consultation	Demonstrated credibility through extensive field studies and external feedback from participants in eKrishi and other ecosystem platforms at a workshop. Criteria for alignment were refined post-consultation, ensuring a nuanced representation of pragmatic interoperability in eKrishi (Field Studies, Multi-stakeholder Consultations)
Transferability	Used theoretical sampling and workshops for broad applicability. Typologies validated against different food data ecosystems. Attended workshops with other ecosystem application owners, validated typologies in industry 5.0 initiatives	Ensured transferability through theoretical sampling and validation in diverse ecosystems. Workshop attendance and typology validation in related initiatives enhanced relevance and broad applicability (Theoretical Sampling, Workshops, Validation in Related Initiatives)
Saturation	Conducted 20 in-depth interviews, follow-ups, and extensive data triangulation. Analysis continued until no new themes emerged	Achieved saturation through thorough interviews and continuous analysis. Comprehensive approach ensured a detailed understanding of eKrishi's pragmatic interoperability with no new insights emerging (In-depth Interviews, Follow-ups, Data Triangulation)
Dependability	Ensured consistent use of detailed study protocols and maintained an audit trail. Shared analysis process with three investigators	Established dependability through meticulous documentation and shared analysis. Protocols and audit trail maintained for reliable and stable findings (Detailed Protocols, Audit Trail, Shared Analysis)
Confirmability	Applied triangulation techniques, interpreter use, and CA approach. Achieved consensus-based interpretation through iterative analysis	Confirmed findings through triangulation, interpreter use, and consensus approach. Minimized biases for a reliable and participant-centric interpretation (Triangulation, Interpreter Use, CA Approach)
Integrity	Triangulated primary data with external sources. Adhered to ethical guidelines in sensitive discussions	Maintained integrity through triangulation with external sources (COSA, FAO, USAID, and CIAT) and ethical guidelines. Avoided biases in discussions on sensitive topics, ensuring authenticity (Triangulation with External Sources, Adherence to Ethical Guidelines)
Fit	Aligned with study objectives, revised alignment criteria, and applied the CA approach	Demonstrated fit by aligning with objectives, refining criteria, and applying the CA approach. Strong alignment and analytical robustness achieved for accurate outcomes (Alignment with Objectives, Revised Criteria, CA Approach)
Understanding	Presented research summaries in multi-stakeholder meetings, conferences, and seminars. Findings well-received, indicating shared understanding	Achieved understanding through positive reception among diverse audiences. Well-received research summaries indicated shared acceptance of outcomes (Research Summaries, Multi-stakeholder Meetings, Conferences, Seminars)
Generality	Employed diverse samples and typologies designed for generality. eKrishi's wide range of modules offered insights into interoperability for different data-sharing motives	Contributed to generality through diverse samples and typologies. Provided insights into common challenges across various food data ecosystems, addressing a wide spectrum of interoperability scenarios (Diverse Samples, Generality-oriented Typologies)
Control	Engaged in collaborative processes and considered various actors' influence	Provided a nuanced perspective on control complexities in eKrishi. Engaged in collaborative processes, considering actor influence for a comprehensive understanding. The study's focus on various modules accounted for the diverse control dynamics in different data-sharing motives (Collaborative Processes, Consideration of Actors' Influence, Module-specific Control Dynamics)

Table 4 Industry 4.0 sustainability and resilience indicators of pragmatic interoperability mapped to eKrishi modules

Indicators	Metrics	Composite indices reviewed	*Pestoscope*	*Geo: Soil, Weather, Crop*	*Roots*	*FPOHub*	*Organic Mandi*	Industry 4.0 value requirements
Social and Human indicators	• Improving access to participatory decision-making and informal safety nets • Education and upskilling towards new applications/information on digital platforms • Improved access to social networks • Fair pricing structure • Access to sufficient food (food security) • Access to safe and nutritious food • Access to portable water. arable land and clean air (quality of life) • Access to technical training and upskilling for climate-smart farming practices	The Global Food Security Index (GFSI) Women's Empowerment in Agriculture Index (WEAI) The Global Hunger Index (GHI) of the International Food Policy Research Institute (Grebmer, 2012)	✓✓✓✓ ✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓ ✓✓✓✓	✓✓✓✓ ✓✓✓✓	Using 4.0 technologies to facilitate interoperability of data for food security analytics (availability, quality, safety, and affordability) 4.0 technologies for analysis and advisory to improve women's engagement in agri-food business based on five pillars: 1. Decision/choice on agricultural production 2. Power of decision making on resources 3. Power of decision making on use of income 4. Community leadership 5. Use of time Applying 4.0 to systematically track and assess global hunger (region/country) using weighted indicators (undernourishment, child underweight, child mortality)
Economic and Financial indicators	• Improving access to supply chain finance (factoring and forfeiting) • Smart insurance for emergencies • Performance monitoring of production and demand to improve access to credits/loans • Data for smart modelling of subsidies and financial assistance from the government • Access to local market data (what crop in demand/price) • Access to digital devices and technologies (including IT and digital applications) to provide farming financial support and advisory	The Rice Bowl Index (RBI)	✓✓✓✓	✓✓✓✓ ✓✓	✓✓✓✓ ✓✓	✓✓✓✓ ✓✓	✓✓✓✓ ✓✓	Applying 4.0 technologies to evaluates/assess: Quantitative econometric data on supply and demand, price, and cost, environmental conditions, farm-level conditions, water scarcity, trade and longitudinal impacts of agri-food policy Qualitative assessments of technological interventions and policy interventions on economic, societal and ecological indicators Socio-economic and socio-ecological assessment of crop production, demand, consumption including debt/asset ratios, returns on investment (ROI), state-level GDP, labour hours, fatalities, and injuries

Table 4 (continued)

Indicators	Metrics	Composite indices reviewed	*Pestoscope*	*Geo: Soil, Weather, Crop*	*Roots*	*FPOHub*	*Organic Mandi*	Industry 4.0 value requirements
Environmental/ecological indicators	• Access to weather forecasting warning systems • Access to weather-proof post-harvest infrastructure • Access to weather-proof transportation infrastructure • Access to digital/smart climate change projections (rainfall/drought, wind speed, humidity, temperature, light) • Access to clean and appropriate farming equipment and technologies • On-farm soil health • On-farm water health • On-farm biodiversity • Access to climate-ready varieties of focus crop • Access to quality planting material for alternative crops • Access to different types of seeds	The National Water Security Index (NWSI) of the Asian Development Bank (2013) The Field to Market index The Global Land Degradation Information System (Field to Market: The Alliance for Sustainable Agriculture, 2021) Integrated Food Security Phase Classification (IPC, 2019) WaterStat (2019)	✓✓✓✓ ✓✓✓	✓✓✓✓ ✓✓✓✓	✓✓✓✓ ✓✓✓✓	✓✓✓✓ ✓		Applying 4.0 technologies to evaluates/assess total national water security based on: 1. Household water security 2. Urban water security 3. Environmental water security 4. Economic water security 5. Water-related resilience (disasters) Applying 4.0 technologies to evaluates/assess Environmental indicators (Energy use, land use, greenhouse emissions, soil erosion, irrigation water)

from Case D that ultimately viewed this to have a negative social impact on the farming community (access of farmers/labour to sufficient and nutrient food (food security).

> *Some of these farmers rely on day to day of* ***selling produces to make ends meet****. [En Primary Value] They also may lack appropriate financial baseline supports, leaving them* ***susceptible to accessing nutrient food for their household [AND S secondary value]***

From an environmental and social perspective not having access to real-time pest and disease data, could result in misuse of such chemicals (how much to use, when to use, quality of pesticide used). This was highlighted by respondent F that argued:

> *Abusing chemical fertilisers and pesticides could harm nontarget organisms and unbalance the pest pressure in nearby/neighbouring farms, contaminate waterways and air quality, cause chronic illness in farm labour and nearby villages/communities, and food residues*

Going forward this could have a huge impact on the farming community, as many of the farmers in this region are marginal and aim to grow their business sustainability and be able to leave their next generations fertile and productive lands. Findings regarding actors' pragmatic intensions for investing in 5.0 technologies for pestcoscope show that while the syntactic and semantic data required for this module reflect environmental values, for farmers pestcoscope primary association is social. Moreover, since pest monitoring does not currently have standardised compliance requirements in the agri-food sector, actors' system-level motivation to invest in SVDT (or defensive data technologies) does not align with the business-level motivation which is centred around using pestoscope for social incentives. This would require technologies that deliver MVDT (e.g., Image processing AI).

6 Socio-economic Interoperability Value

6.1 FPO Hub – Farmer Producer Organisation Management

An FPO is a legal entity/cooperative society/company shaped by primary producers (farmers) to share benefits/profits and minimise risks among its members. It helps the more vulnerable small farmers and safeguards them by attaining the benefit of economies of scale (may not have the required capacity individually). Furthermore, in the Indian agriculture sector, a long chain of agents and intermediaries exist quite often working without much regulation often leading to the producers getting only a small portion of the value end consumer pays. Such entities could also help with negotiating with bulk upstream suppliers (raw material procurement for farmers) and large-scale downstream buyers. Respondent E highlighted some of the key data streams required for FPO hubs in supporting and achieving farming sustainability initiatives.

> *"a successful FPO aimed at improving sustainability in the farming sector would have information and data on legal compliance (registration, taxation), support services (credit and insurance and market data), and other Enterprise Resource Planning (ERP) for FPO management"*

As noted above Enterprise Resource Planning (ERP) for FPO management could be key at achieving sustainability at the farm level, using farmers themselves. Data streams such as membership, accounting, share capital, loans (and finances), production and business planning, inventory/stock management, custom hiring of machinery and services, transactions and legal compliances (tax compliance, Annual returns) could help in this regard.

7 Organic Mandi (Virtual Marketplace for Organic and Conventional)

Another critical data stream identified through our interviews was related to the marketing and selling of the crop online. Indian farmers suffer greatly from the disintegrated supply chain and the number of the different agents they could potentially deal with. The livelihoods of these farmers could vary significantly, depending on their proximity to a particular VLPC, the government logistics support provided, and direct/indirect access to the market. As such, there is a need for a could base Virtual Farmers' Market (VFM) application where farmers' surplus and buyers' demand for crops are marketed and transacted. Regarding the importance of developing such an online platform is moving towards sustainability of farmers, respondent J explained that:

> *"Online virtual market platforms could provide a transparent, trustworthy, and open environment for smallholder farmers and buyers to negotiate fair prices and deals, which may not be possible physically. It could help smallholder farmer's better estimate their production and selling price, and market this data online and in real-time"*

8 Eco-efficiency Interoperability Value

8.1 Geo (Soil, Weather, Crop monitoring)

One of the other important data streams rendered significant for sustainable farming is access to real-time weather (monitoring) data. In this regard, respondent E explained that:

> *Unlike other sectors, weather directly affects farming productivity as it impacts crop growth, the farming yield, the number of pest incidence, and the number of critical resource/inputs required pesticide, and water for irrigation*

This has become even more significant as climate change and its unpredictability is beyond human control. However, with access to accurate weather data and additional farm management practices, farming activities could be calculated without adverse incidents (minimise crop losses and improve yield). The problems with climate change were also reflected by respondent A3 that highlighted:

> *"During the past 5 year's drought has become our nightmare and major problem for us. Especially dealing with high water-consuming produces such as tomatoes. We now have additional challenges and require more investment in automatic water pumping technologies."*

Respondents further noted that soil management practices not only maximise the output of agricultural produces but also help reduce environmental pollution which is a major challenge affecting farmers wellbeing and livelihood. In this regard, respondent D stressed that: "*We need information to help us protect from soil erosion to avoid more soil degradation and contamination"*.

Furthermore, most respondents interviewed considered both land degradation and soil erosion as acute threats to their ecosystem and farming productivity, for instance respondent A3 noted that: *"We do not care so much about increasing our output capacity but to make sure we have fertilised lands to handover to our next generation"*.

As shown in the quotes above, the primary association that influences farmers pragmatic views on Geo data interoperability is environmental. However, value emphasised by each respondent is economic. For instance, respondent D emphasised "*avoid more soil degradation and contamination"* while respondents A3 spoke about economic implications of handing over "*fertilised lands … to our next generation*". We further found that this eco-efficiency association is especially greater in in tropical regions (e.g., Hyderabad), where such a loss of natural capital (non-renewable) assets is more likely to occur due to flooding, soil run offs from erosions and poor vegetation cover.

9 Roots (Source Traceability)

Another key data stream deemed important in improving farmer's sustainability was source traceability. In simple terms this refers to the capability to trace the harvested goods using data on production and demand histories, location, capacity, variety, type of production (conventional – organic) by means of recorded identification (e.g. IoT, RFID devices containing real time data on these categories). Regarding the impact of source traceability and sustainability and resilience metrics for informing industry 5.0 investment, respondent A4 explained that:

> *"Indicating what type of grow practice we adopt (organic or conventional), helps us effectively market and sell our crop. If our customers know the extra costs associated with organic practices and the health benefits, they could be motivated to pay more for our organic produce"*.

As noted by the respondent above, the source of traceability not only improves farmers financial and market value (sales of organic produce) but also has cross-cutting economic impacts (e.g. preserving land for future generational use (more fertile), creating on farm employment and improving smallholder household income). In this regard, respondent A4 highlighted the economic association with GEO that impacts public entities pragmatic incentive to invest in 5.0 technologies for data and metrics interoperability noting that *"VLPC would need to know when our crops are harvested and gathered from the fields. This could help them know when and how much we produce."*

This type of information can help collection centres and aggregators better manage their downstream supply chain (providing retail customers with up-to-date or live data on the season of harvest, how much can be supplied). Using different agricultural data management initiatives in source traceability, respondent E asserted that:

> *"Geo-tagging of plots is an essential step in digitizing the Indian agri-food supply chain, we are now in the process of using/integrating geographical identification metadata to different media such as electronic messages, websites, QR Codes, geotagged video and photos"*

Regarding the Roots module on eKrishi (source traceability), our findings are counterintuitive, because traceability in food chains, as argued in the literature review, is primarily driven by provenance and safety compliance to a large extend and recently by customers' requirements. However, in this case because of the context where there are no strong regulatory or compliance requirement for traceability, the pragmatic motives of actors to invest in industry 5.0 technologies is eco-efficiency where government actors pursue economic value for society (e.g., improved employment) while private actors pursue financial value for their business (e.g., better ROIs for organic agriculture investment).

9.1 Aligning System and Business-level Pragmatic Interoperability: Requirement and Challenges

Requirements for system and business interoperability cover actors' contextual considerations of location, stakeholder needs, motivations and intentions, constraints, and limitations. When asked about what they want from interoperable 5.0. systems and technologies, in terms of resilience and sustainable farming, respondent A1 explained.

> *"All we want is to live decent lives and take care of our lands for future generations……. What we really need now are technologies we can use on apps to inform us on how to improve our lands plan better and maintain our livelihoods"*

There was consensus that the core system value of interoperable technologies is improving the livelihood of farmers and the socio-ecological (capture value from the sale of sustainable produce) and ecoefficiency value in the supply chain (Reduce/eliminate food loss). When asked about the key requirements for investing in digital platforms, Respondent A5 answered.

> *"Before I signed up on the platform, I faced many problems with plant disease and didn't know which pesticide was best to use. I can take pictures of my ill vegetables and upload it…. I get an alert on my mobile on what to use)"*

Likewise, respondent A2 explained:

> *"The soil monitoring app and source traceability helps me understand my land better…I have started organic farming as a result… but getting into the market is hard and margins are low…I could get a loan from our cooperative, but I have to plan ahead for next season., if the app will help me sell online to big retail giants, so that our produce was viewed and bought by more people"*

The prevailing norms around the role of digitised data is that it helps improve yield of production, variety of produce, inputs costs, method of farming (organic, conventional), waste amongst other important actions, which are viewed not viewed as environmental, social or economic but as **aggregate intended goals** (e.g., produce reaching consumers). Regarding this, respondent G noted:

> *"The platform was developed with the intention of improving farming sustainability, and much has been done to capture inputs at upstream activities. To realise the full triple bottom line potential, it could be beneficial if we could work closer with the retail and business end and to explore possibilities of integrating our platform with their own digital ERP/SAP systems"*

Respondent G explained that the platform was designed to digitise farmers key data requirements by integrating technologies that are suitable for each tier of actors. While farmers still rely on manual data, aggregators and retails have ERP systems and use RFID and barcodes for logistics track and trace. These same technologies could be used to facilitate greater interoperability by valuable information to actors in other tiers without the added investment and adoption costs. To this end, respondents emphasized the role of collaborative technology design, noting that:

> *"We are happy to see and work with developers of new and innovative applications/platforms and are willing to collaborate and share data sets on public investments, subsidies, agricultural credit, crop and livestock insurance, that are required in tracking the performance of public support service to our farmers"*

Likewise, Respondent I emphasized the role of developers co-creating technologies to enable them use the data currently available to them to pursue more innovative strategies, They moted that:

> *"This is a new platform we are using. It is quite a user friendly and has very useful applications such as weather forecasting, soil monitoring and pest control. However, it could improve by connecting us to major retail and outlets, this is missing"*

As highlighted above, the platform has not scaled to a degree that can support end-to-end sharing of information among Farm, VLPC, and retail sub-systems (universal understanding/ processing of data/info using cooperating platforms). In this regard, respondent E explained:

> *"We are yet to get to that stage of integrating our system/databases with organisations outside our own supply chain. We are putting in place provisions to account for cross-boundary data and information integration"*

In this regard, developers acknowledged that integrating the platform with other systems outside their own supply chain, would raise challenges at the level of data handling and storage and access, hence, collaborative structures are required to develop service level agreements for pragmatic interoperability based on actors shared perceptions on platforms, and data architecture requirements and applications.

9.2 Summary of Findings

Summarising the study findings on the values actors ascribe to system and business-level interoperability data and technologies, we argue where food chain actors associate environmental metrics to other measures, for instance associating Pest analytics to "Environment AND Society" or "Environment AND Economy", the pragmatic value association of compliance (e.g., investment in SVDT infrastructure) underpins pragmatic interoperability at business and system-levels if compliance structures (regulations) are in place or being developed. Tensions in pragmatic interoperability at system and business-levels arise when environmental values are commingled with others economic or societal values, in the absence of local or global regulatory or compliance incentives.

Similarly for modules where the primary syntactic and semantic associations are economic or financial, actors are inclined to view such measures as requiring multiple versions of the truth (offensive data strategy). However, the secondary association is important here. If it is an eco-efficiency association, actors' pragmatic interoperability at business and system-levels are aligned when there are regulatory structures and market incentives. If regulatory structures are available but the market incentives are unproven, then actors' pragmatic interoperability would tend towards a defensive data strategy (SVDT strategy). Without regulatory structures, clear economic incentives and collaborative structures to define them are required, otherwise, actors' pragmatic intentions to invest in 4.0 technologies at the system and business-levels are misaligned, leading to disparate defensive and offensive data strategies.

Likewise, we find that for metrics, or modules where the key association societal, actors' pragmatic interoperability is inclined towards 4.0 capabilities for a multiple version of truth offensive data strategy. Societal measures of value such as poverty alleviation, employment, health and safety, food security and so on require a multiple version of data truth strategy, however, if paired with a strong compliance association, we find that the actors are pragmatically inclined towards 4.0 technologies that facilitate compliance reporting and technologies that provide a SVDT strategy. Unlike environmental and economic metrics, compliance and economic incentives alone appear to be insufficient to drive alignment in social measures. For instance, poverty, food security, workers welfare and so have varying secondary associations to the economic and environmental concerns of actors in their local contexts. Hence, we find that what is required to align actors' system and business-level pragmatic interoperability considerations for social measures are local structure or bottom-up collaborative data governance mechanisms for alignment on these measures.

10 Discussion

10.1 RQ1: System and Business Value for Pragmatic interoperability in Food Data Ecosystems

The SSOT (Single Source of Truth) architecture for data defense strategy aimed at compliance and the MOVT (Multiple Versions of the Truth) architecture for data offense are key theoretical paradigms in the literature on data strategy used to explain how organizations use data and technology to meet business needs (DalleMule & Davenport, 2017). In the literature on interoperability, we identified parallel theoretical arguments in the understudied dimension of pragmatic interoperability. The alignment of intended and actual use of data is fundamental for ensuring that technical, syntactic, and semantic data and technology infrastructure are used effectively by stakeholders. Our review highlighted Asuncion and van Sindere's (2010) framework, which categorizes pragmatic interoperability into system level and business level, to assess different aspects of actors' pragmatic motives that reflect their willingness to interoperate at system and business levels.

Our exploration into the first research question focused on understanding how actors perceive system-level and business-level interoperability in the context of the eKrishi platform. Our findings revealed that system-level motivations often align with SSOT principles, emphasizing compliance and standardization. For example, the Pestoscope module aggregates data on pest prevalence to develop standardized environmental metrics, embodying the SSOT approach which emphasizes data accuracy and consistency to ensure reliable environmental monitoring (Brewster et al., 2017; Glaros et al., 2023). However, actors using the Pestoscope module prioritize socio-ecological benefits, seeking actionable insights that blend environmental data with social and economic considerations. This discrepancy highlights a key tension: the SSOT architecture must first collect comprehensive environmental data, whereas the actors require integrated analytics that provide immediate, practical value.

This tension is further exemplified by the Organic Mandi module, designed to facilitate market access for organic farmers through compliance with multiple certification schemes, aligning again with SSOT principles. Large Farmer Producer Organizations (FPOs) using this module aim to enter international markets, necessitating integrated data stacks that meet diverse regulatory demands. Conversely, small-scale farmers focus on reducing waste and improving local market access, emphasizing socio-economic benefits that blend various data types. This divergence underscores the challenge of meeting both system-level compliance and business-level market needs within a single platform

(Bai, 2021; Joo et al., 2018). The eKrishi platform's FPO Hub module is another example. It aggregates data from smallholder farms to provide advisory services on income, credit, sustainability, production system planning, access to markets, and traceability. The SSOT framework here ensures accurate and standardized data collection, crucial for financial and production planning. However, farmers using the FPO Hub prioritize immediate socio-economic benefits such as improved market access and income stability, which requires dynamic and context-specific data analytics that align with MOVT principles (Narwane et al., 2022; Sugandh et al., 2024). The Geo module, which provides geospatial data for optimizing resource use, embodies the SSOT approach by integrating standardized environmental data. This data is essential for long-term sustainability planning and compliance with environmental regulations. However, farmers and agribusinesses using the Geo module seek eco-efficiency benefits, such as optimized irrigation and fertilizer use, which require real-time, localized data analytics that align with MOVT principles (Kamilaris et al., 2017; Šestak & Copot, 2023). Similarly, the Roots module, designed to enhance traceability and sustainability in supply chains, relies on SSOT principles to ensure data integrity and regulatory compliance. However, actors in the supply chain prioritize socio-economic benefits, such as improved product differentiation and market responsiveness, which require integrated data analytics that provide comprehensive insights across various data types (Dooley et al., 2018; Panwar et al., 2023).

10.2 Contribution of RQ1

DalleMule and Davenport (2017) argued that less than half of an organization's structured data is used in decision-making, and less than 1% of unstructured data is analyzed. This reflects broader challenges faced by platforms like eKrishi. While the Pestoscope module integrates multiple versions of the truth through imaging analytics, farmers demand higher granularity. They seek individualized data, underscoring the tension between SSOT's aggregated datasets and MOVT's personalized insights. Even with strides to balance SSOT and MOVT, there remains a persistent push toward business-level requirements that the system-level design struggles to accommodate fully.

Our study extends the literature by demonstrating that while a hybrid strategy blending SSOT and MOVT is ideal, practical application requires understanding the trade-offs between system and business-level interoperability. Developers of Industry 4.0 platforms must prioritize MOVT capabilities from the outset, integrating analytics that align with business-level pragmatic interoperability motives. For instance, environmental modules like Pestoscope should deliver eco-efficiency or socio-ecological insights to meet actors' needs. This approach is crucial for designing effective Industry 4.0 solutions that balance compliance and dynamic business needs (Leong et al., 2023; Renner et al., 1996).

Reflecting on the theoretical implications, our study suggests that the integration of SSOT and MOVT strategies necessitates a nuanced understanding of how these paradigms interact in practice. System-level motivations, driven by the need for compliance and data standardization, often lead to the initial prioritization of SSOT architectures. This is essential for establishing a reliable foundation of data integrity and regulatory adherence. However, as DalleMule and Davenport (2017) highlight, the reality is that much of this data remains underutilized, with significant portions of unstructured data left unanalyzed. This underutilization is a direct result of the system-level focus on data aggregation and compliance, which overlooks the immediate, practical needs of business-level actors.

In practical terms, the eKrishi platform's challenges reflect these issues vividly. The Pestoscope module, for example, has made significant strides in integrating MOVT by incorporating imaging analytics. However, the actors require even higher levels of granularity, such as individualized data capture on farms, which goes beyond the system's initial SSOT design. This reflects a broader industry challenge: while the intent to integrate MOVT exists, the execution often falls short due to the inherent limitations of SSOT architectures (Poppe et al., 2013; Schuurman, 2002).

These findings align with the literature on semantic, syntactic, and technical interoperability, which often assumes that establishing these foundations will naturally lead to effective business-level interoperability (Kayikci et al., 2020). However, our study reveals that pragmatic interoperability at the business level requires more than just a solid technical foundation. It demands a deliberate focus on delivering the immediate, actionable insights that actors prioritize. This insight bridges a critical gap in the literature, emphasizing the need for Industry 4.0 developers to map early on which MOVT elements their SSOT can deliver, ensuring alignment with business-level needs (Falconer Hall et al., 2024; Muniz et al., 2021). For example, the Organic Mandi module aimed at aggregating organic farmers and facilitating market access highlights the importance of balancing system and business-level needs. Large FPOs require sophisticated data integration to meet international standards, while small-scale farmers seek localized analytics for market entry. The differing needs of these actors create tensions that the platform must navigate, reflecting broader industry challenges in achieving pragmatic interoperability (Narwane et al., 2022; Sugandh et al., 2024).

Our findings underscore the necessity of a hybrid strategy that blends SSOT and MOVT from the outset. By understanding the specific pragmatic needs of business-level actors and ensuring that system-level architectures can support these needs, Industry 4.0 platforms can enhance adoption and scalability. This approach not only meets compliance requirements but also delivers tangible business value, ensuring the long-term success of these technologies.

10.3 RQ2: Typologies of System and Business Value Alignment for Pragmatic interoperability in Food Data Ecosystems

Our second research question focused on understanding how actors navigate the trade-offs between system-level and business-level interoperability within the context of Industry 4.0 technologies. DalleMule and Davenport (2017) discuss the necessity of balancing Single Source of Truth (SSOT) architectures for defensive strategies and Multiple Versions of the Truth (MVOT) architectures for offensive strategies. Our study extends this discussion by revealing how these trade-offs are managed in practice, particularly within the agri-food sector.

Since we engaged with a diverse range of actors, including technology developers, financiers, government officials, and end-users, we were able to capture varied perspectives on system-level and business-level pragmatic interoperability. These actors often highlighted either system-level or business-level considerations more prominently, which allowed us to categorize them into different quadrants based on their main focus. This categorization revealed insightful patterns about how these actors negotiate the tensions between their business and system needs.

Our analysis led to the development of a 2 × 2 framework categorizing actors based on their emphasis on system-level and business-level interoperability (see Fig. 2). This framework includes the following quadrants: ***Corporate Citizenship Pragmatic Interoperability***, ***Regulatory Stewardship Pragmatic Interoperability***, ***Corporate Stewardship Pragmatic Interoperability***, and ***Value Chain Stewardship Pragmatic Interoperability***.

Actors in the ***Corporate Citizenship quadrant***, such as large Farmer Producer Organizations (FPOs) oriented towards international markets, large processors, and producers, prioritize extensive technological integration and compliance with international standards. For these actors, their trade-off entails high system-level and lower business-level pragmatic interoperability to adopt 4.0 technologies. These actors face significant challenges in balancing voluntary and centralized standards to enter different markets. Large sustainability-based FPOs, for instance, seek to unify governance frameworks like ISO standards and the Global Reporting Initiative to meet diverse regulatory requirements. However, the contention between voluntary and centralized standards often creates onboarding challenges, as these actors need integrated data systems that can seamlessly navigate multiple market requirements. The Organic Mandi module on the eKrishi platform exemplifies these challenges by attempting to aggregate organic farmers under certification schemes. While large FPOs can use the Organic Mandi to align with international organic standards, smaller FPOs struggle with these stringent requirements due to limited resources, highlighting the need for integrated data stacks that support both voluntary and centralized standards.

A broader look at other Industry 4.0 initiatives reveals similar challenges. For instance, in the manufacturing sector, companies face similar tensions in balancing compliance with different international safety and environmental standards while trying to innovate and enter new markets (Beck et al., 2017). The need to integrate various regulatory requirements with innovative business strategies highlights the universal nature of these challenges.

Government regulators, government financial bodies (NABARD), and certification bodies fall into the ***Regulatory Stewardship quadrant***, focusing on system-level data integration to ensure compliance and policy enforcement. They value platforms providing robust, standardized data for policy-making and strategic oversight, such as the Roots module for traceability and compliance. Their trade-off involves high system-level and lower business-level pragmatic interoperability. Their siloed nature and disparate data sets pose challenges in achieving holistic interoperability. Certification bodies working with the eKrishi platform aim to enforce compliance metrics across the supply chain, but their focus on system-level interoperability often clashes with the dynamic needs of small farmers who require more flexible, context-specific solutions. This tension highlights the difficulties in achieving comprehensive regulatory compliance while addressing the immediate needs of diverse stakeholders.

In the healthcare sector, regulatory bodies face similar challenges. The integration of electronic health records (EHR) across different healthcare providers often leads to issues of data standardization and interoperability. The need for compliance with health data regulations like HIPAA in the U.S. while trying to integrate innovative health technologies mirrors the tensions seen in the agri-food sector (Weber & Kuziemsky, 2019).

Corporate Stewardship Pragmatic Interoperability actors, including multinational companies and larger FPOs, aim to consolidate reporting for regulatory and market compliance. They leverage platforms like the FPO Hub to improve reporting quality to stakeholders, including financiers and consumers. For these actors, the trade-off requires high system-level and moderate business-level pragmatic interoperability. However, varying reporting requirements create challenges. While a farmer might prioritize regulatory compliance, a retailer might focus

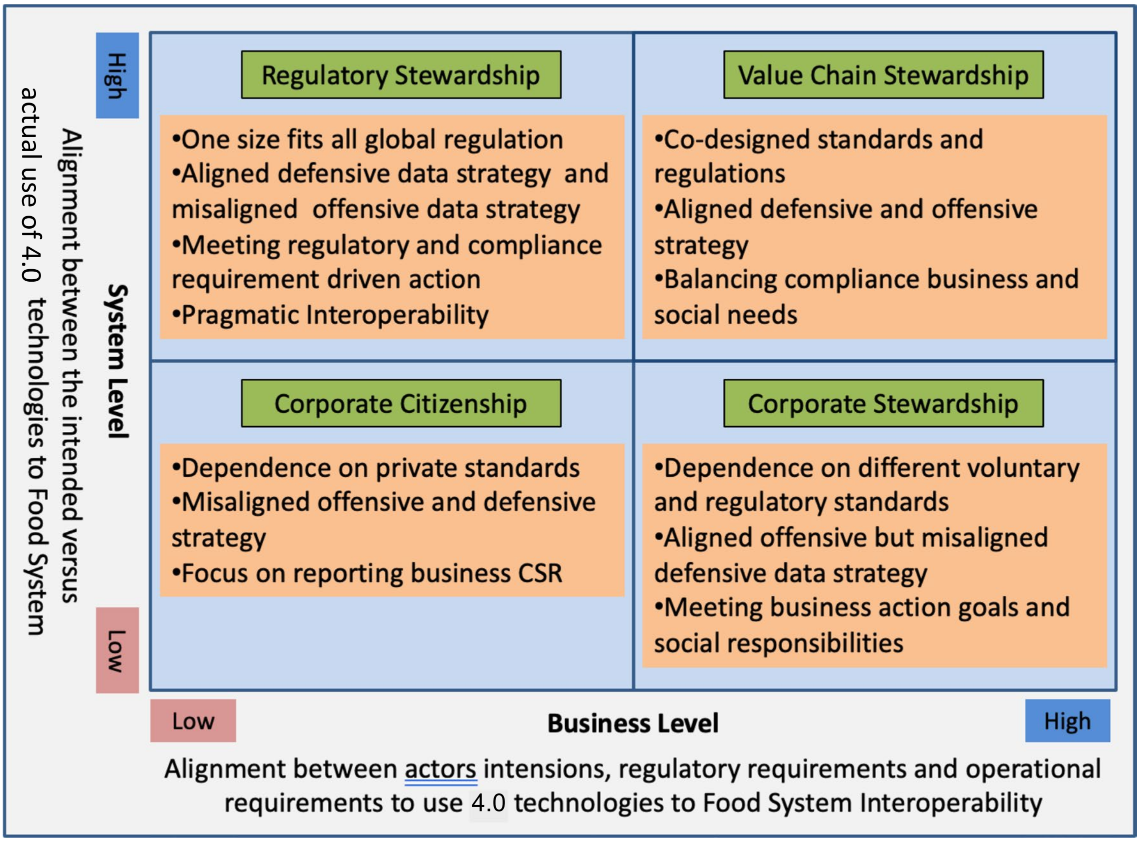

Fig. 2 Conceptual Framework for System and Business Pragmatic Interoperability Alignment

on market responsiveness. Zambon et al. (2019) and Giaffreda et al. (2016) highlight these discrepancies, showing that although interoperability can facilitate comprehensive reporting, the perceived value varies significantly among actors.

Multinational companies and larger FPOs focus on integrating multiple reporting standards to satisfy diverse stakeholder requirements. Platforms like FPO Hub facilitate this by offering comprehensive reporting tools catering to regulatory and market needs. However, the variation in reporting requirements across different stakeholders remains a challenge. For instance, financiers might demand detailed financial reports, while consumers seek sustainability metrics. Despite the availability of integrated reporting tools, actors struggle to balance the varying demands, leading to partial adoption and utilization of these tools.

In the financial services sector, similar issues arise with multinational banks needing to comply with various international financial reporting standards while also catering to different stakeholder requirements. The integration of diverse reporting standards into a single cohesive system remains a significant challenge, illustrating the broader applicability of our findings (Panwar et al., 2023).

Small farmers, small and medium FPOs, NGOs, and local government bodies fall into the ***Value Chain Stewardship quadrant***, emphasizing immediate socio-economic benefits and local market access. These actors prioritize dynamic, context-specific advisory services and actionable insights to improve livelihoods and market access. Their trade-off entails lower system-level and higher business-level pragmatic interoperability. Small farmers using the eKrishi platform seek to reduce waste and improve local market access through tailored advisory services. The Value Chain Stewardship approach highlights the need for flexible data systems that can adapt to the specific needs of smallholders, contrasting with the rigid, standardized data requirements imposed by system-level interoperability frameworks.

In the retail sector, small and medium-sized enterprises (SMEs) face similar challenges when adopting new technologies to improve supply chain efficiency. The need for scalable solutions that provide immediate benefits is critical, yet many SMEs struggle with the resource demands of integrating these technologies into their operations.

Our findings reveal that the challenges of navigating these trade-offs are deeply rooted in the inherent tensions between SSOT and MVOT architectures. For instance, while the

Pestoscope module integrates multiple versions of the truth by incorporating imaging analytics, it struggles to meet the high granularity demands of individual farmers who require specific pest management solutions. This reflects the broader issue identified by DalleMule and Davenport (2017), where significant time and resources are spent on data preparation and integration, leaving little room for delivering the tailored analytics that business-level actors demand.

Financiers and insurers on the eKrishi platform also face significant challenges in balancing system and business-level interoperability. While they require standardized data for risk assessment and compliance, they also need dynamic, context-specific insights to evaluate financial risks and opportunities effectively. This dual requirement often leads to tensions in data prioritization and integration, reflecting the broader trade-offs in data strategy.

Our study extends the literature by providing a pragmatic interoperability framework that bridges data strategy and interoperability theories. By highlighting the distinct offensive and defensive strategies employed by different actors, we offer a nuanced understanding of how these strategies can be aligned to achieve comprehensive interoperability. This framework can guide future research in exploring the alignment of system and business-level strategies in various Industry 4.0 contexts.

Furthermore, our findings suggest that developers of Industry 4.0 platforms need to consider the pragmatic interoperability motives of different actors early in the design phase. Mapping the first set of MVOT elements that their SSOT can deliver is crucial. For example, the Pestoscope module on the eKrishi platform included efforts to integrate imaging analytics to meet the multiple versions of truth requirements. However, the complexity of standardizing and expanding these capabilities highlights the need for a balanced approach that considers both SSOT and MVOT architectures from the outset.

For policymakers, the framework helps design regulations that consider the diverse needs of different actors, promoting more inclusive and effective governance. By identifying the position of different actors and adjusting strategies to better navigate the trade-offs between system-level and business-level interoperability, policymakers can foster an environment conducive to the adoption and effective use of Industry 4.0 technologies.

Additionally, the study contributes to advancing the understanding of how actors make trade-offs between defensive and offensive strategies in pragmatic interoperability. Future research can build on these findings by exploring how different actors prioritize and balance these strategies in various contexts, addressing questions such as: How do different regulatory environments influence the adoption of Industry 4.0 technologies? What role do cultural and organisational factors play in shaping pragmatic interoperability motives? Exploring these questions can further elucidate the complex dynamics of pragmatic interoperability and its impact on technology adoption and use in diverse settings.

10.4 Theoretical Contribution

The study contributes to advancing our understanding of pragmatic interoperability in the context of Industry 4.0 technologies, specifically within the agri-food sector. Through the application of conversation analysis (CA) and thematic coding, we offer new insights into how diverse actors—ranging from smallholder farmers to large agribusinesses—construct, negotiate, and align their pragmatic motivations for engaging with digital platforms. This contribution is threefold, focusing on the conceptualization of pragmatic interoperability, the interplay between system-level and business-level motives, and the methodological implications for analysing conversational data in complex, multi-actor environments. The study reconceptualizes pragmatic interoperability by framing it not merely as a technical or semantic alignment issue, but as a dynamic process involving multiple stakeholders with varying strategic objectives. Previous literature on interoperability has largely focused on the technical and syntactic levels, often neglecting the nuanced, pragmatic dimensions that shape how and why actors engage with interoperable technologies. By examining how actors use logical operators like "AND" and "OR" to discuss and prioritize different modules of the E-Krishi platform, the study elucidates how pragmatic considerations—such as perceived value, risk tolerance, and strategic goals—drive technology adoption and use. This reconceptualization expands existing theoretical frameworks by emphasizing the critical role of human agency, contextual dynamics, and actor-specific motivations in achieving interoperability. The study makes a theoretical contribution by bridging the gap between system-level and business-level interoperability motives, which have often been treated in isolation in the literature. By developing a 2 × 2 framework that categorizes stakeholders based on their pragmatic interoperability motives at both the system and business levels, the study provides a novel approach to understanding how different actors align or diverge in their use of interoperable technologies. This dual focus challenges the dominant view that system-level interoperability automatically leads to business-level benefits. Instead, the study demonstrates that actors often negotiate complex trade-offs between these levels, influenced by factors such as resource availability, market conditions, and organizational priorities. This theoretical insight adds depth to existing models of technology adoption by highlighting the interplay between macro-level systems integration and micro-level business strategies. The study also contributes methodologically by integrating CA with thematic coding to analyze conversational data in a complex, multi-actor setting. While CA has been widely used to explore the structure and organization of talk (Schegloff, 2007), its combination with thematic analysis represents a novel approach that enables the identification of broader patterns and themes without losing the richness of interactional details (Heritage & Clayman, 2010). This methodological innovation allows for a more holistic understanding of how actors construct meaning and negotiate value around interoperable technologies. By capturing both the micro-level details of conversation and the macro-level themes that emerge across multiple data sources, the study offers a more comprehensive framework for analyzing stakeholder engagement with digital platforms. This approach can be applied in other sectors where technology adoption involves multiple actors with divergent interests, providing a robust method for uncovering the hidden dynamics of stakeholder interactions.

Furthermore, the study contributes to the broader discourse on Industry 4.0 solutions by demonstrating how digital platforms can be strategically positioned to meet the diverse needs of stakeholders in highly fragmented sectors like agri-food. Previous studies have highlighted the challenges of implementing Industry 4.0 technologies in sectors characterized by complex supply chains, power asymmetries, and varied levels of technological maturity. By focusing on the E-Krishi platform, the study illustrates how pragmatic interoperability can serve as a strategic lens for understanding and addressing these challenges. The findings suggest that successful deployment of Industry 4.0 solutions requires not just technological integration, but also an alignment of diverse actors' motives and goals through tailored platform features and functions. This contribution is particularly valuable for researchers and practitioners seeking to understand the factors that drive or hinder technology adoption in complex, multi-actor ecosystems. Finally, the study lays the groundwork for future research on pragmatic interoperability by offering a new conceptual and methodological framework that can be applied in different contexts and sectors. It encourages further exploration of how digital platforms and interoperable technologies can be designed and deployed to accommodate diverse stakeholder needs and strategic intentions. Practically, the study provides actionable insights for technology developers, policymakers, and industry practitioners, highlighting the importance of engaging with multiple stakeholders and understanding their specific motivations and constraints to enhance the adoption and impact of digital solutions.

10.5 Limitations and Future Research

While our study offers valuable insights into the pragmatic interoperability dynamics within the context of Industry 4.0 initiatives like eKrishi, it is essential to acknowledge certain limitations that shape the scope and generalisability of our findings. The study's focus on the eKrishi platform and its specific modules may limit the transferability of our results to other Industry 4.0 contexts. Different platforms and technologies may exhibit distinct interoperability challenges and motivations, influenced by factors such as sectoral differences and geographical variations. Additionally, the study's cross-sectional nature provides a snapshot of the pragmatic interoperability landscape at a specific point in time. The dynamic nature of technology and evolving business practices implies that these findings might not capture potential changes or dynamic developments in the field.

Future studies could delve into addressing the limitations of this research, considering diverse industry contexts and additional ESG dimensions. A critical exploration of how various industries, beyond the food sector examined in this study, map onto the identified alignment typologies could provide valuable insights. Investigating how different ESG considerations interact with and influence the deployment of technology, particularly in terms of control (SSOT) and flexibility (MVOT), would enhance the generalisability and applicability of the proposed framework. This avenue of research would contribute to a more comprehensive understanding of pragmatic interoperability in the broader landscape of digital ecosystems, offering nuanced insights tailored to distinct industry and ESG contexts.

11 Conclusion

Our study reveals that the primary trade-offs between system-level and business-level interoperability in Industry 4.0 technologies hinge on the alignment between SSOT (Single Source of Truth) and MVOT (Multiple Versions of the Truth) data strategies. We found that while system-level interoperability focuses on defensive strategies for data consistency and compliance, business-level interoperability prioritizes offensive strategies for flexibility and context-specific insights. These findings provide a new framework for understanding how different actors, including large and small FPOs, government regulators, multinational companies, and small-scale farmers, navigate these trade-offs in complex ecosystems. The broader implications of this research highlight the necessity for tech developers, policymakers, and businesses to map and integrate MVOT capabilities early in the design phase of digital platforms to ensure comprehensive interoperability and higher adoption rates.

The framework elucidates how actors balance system and business needs, offering a lens to explore regulatory, market, and operational challenges across various sectors. Future research could investigate how different regulatory environments and cultural contexts influence these trade-offs, addressing questions about the impact of regulatory landscapes and organizational culture on technology adoption. Limitations of this study include its focus on the agri-food sector, potentially limiting the generalizability of findings, and the cross-sectional nature of the data, providing a snapshot rather than a longitudinal view. Future work could refine our framework by incorporating longitudinal studies and examining its applicability in other sectors, enhancing our understanding of pragmatic interoperability in diverse digital ecosystems.

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Data Availability The data generated during this study include qualitative transcripts, audio recordings, researcher-generated logs from site visits, mind maps, and other materials created during the research process. Due to the sensitive and confidential nature of these materials, they are not publicly available to safeguard participant privacy and comply with ethical guidelines. However, the data may be made available from the corresponding author upon reasonable request, subject to compliance with ethical and legal standards, and with the approval of the relevant ethics committee if required.

Declarations This study was conducted in accordance with the ethical standards outlined by Research Councils UK (RCUK), the General Data Protection Regulation (GDPR), the Economic and Social Research Council (ESRC) Framework for Research Ethics, and the Declaration of Helsinki. Ethics approval was obtained as part of the Project Transsition initiative, under grant approval number [ST/T001313/1; ST/T001313/2], by the Ethics Committee of the University of Sheffield. The study also complies with the principles of the Committee on Publication Ethics (COPE). All participants provided informed consent to participate in the study, including the collection and use of their data for research purposes.

Consent for Publication All participants were fully informed about the nature and scope of the research, including its potential for publication. Participants provided explicit consent for the publication of anonymized data, ensuring that their identities and any sensitive information remain protected. The consent process included a detailed explanation of how the findings, recordings, and analyses would be used in publications, presentations, and other academic outputs. Participants were given the opportunity to ask questions and withdraw consent at any stage before data anonymization, and all decisions to participate were voluntary.

Competing Interests We declare that there are no competing interests relevant to the content of this article and that this article has not been submitted anywhere else.

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