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Unpacking smart farming innovation: A systematic literature review on technological change in agriculture

Lea Daniel [a], Lars Groeger [b,c], Katharina Hölzle [a,d,*]

[a] *Institute for Human Factors Engineering and Technology Management, University of Stuttgart, Germany*
[b] *Macquarie Business School, Macquarie University, Australia*
[c] *ICN Business School, France*
[d] *Fraunhofer Institute for Industrial Engineering, Stuttgart, Germany*

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ABSTRACT

Technological change presents significant challenges for organizations and society and needs to be understood from a socio-technical perspective. Technology and Innovation Management (TIM) can play a crucial role in understanding disruptive change. Smart farming technologies (SFTs) are used as prime examples for disruption in a traditional industry. This paper shows how scholars can use TIM theories to contribute to a better understanding and subsequent recommendations for action. We review 973 articles using bibliographic coupling to synthesize existing literature. We identify the most prominent research themes and problematize the existing narratives in light of three theoretical approaches to technological change: evolutionary economics, social construction of technology, and actor-network theory. Finally, we present theory-driven questions for future research that indicate new directions for TIM. We comprehensively review and synthesize existing research at the intersection of smart farming technologies and the TIM domain, using bibliographic coupling to identify prominent research themes, highlight blind spots, and generate questions for future research. To counter the common shortcomings of systematic literature reviews in general (Alvesson and Sandberg, 2020) and trending automated literature reviews, we supplement our analysis with an extensive explorative-qualitative discussion of the results, linking our findings back to theory and deriving a comprehensive set of research questions for future research. We build upon Bruun and Hukkinens' (2003) Integrative Framework for Studying Technological Change to guide our discussion and expand our critical review. Thus, we make three main contributions. First, we give a curated and comprehensive overview of articles on SFT and technological change to identify the theoretical deficiencies that lead to oversimplified assumptions regarding the dissemination of smart farming technologies. Second, we enrich the TIM literature by applying three established theories of technological change in a particular sector, making the connection between a specific domain of technological application (SFT) and established theories in the technology and innovation management field. Third, by detailing the extent to which the three theories help us understand the existing literature and discussing it in its entire complexity, we identify several blind spots of current research and derive research questions for future research in both, the SFT and the TIM field. This approach opposes a technology-deterministic and simplistic view of technological developments. By doing so, we aim to inspire TIM scholars to use theories that sharpen their understanding of the socio-technical system

* Corresponding author at: Institute for Human Factors Engineering and Technology Management, University of Stuttgart, Germany.
E-mail addresses: lea.daniel@iat.uni-stuttgart.de (L. Daniel), lars.groeger@mq.edu.au (L. Groeger), katharina.hoelzle@iat.uni-stuttgart.de (K. Hölzle).

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and the complexity of technological change. The article is structured as follows: we present the current state of smart farming adoption and diffusion, introduce the theoretical framework, describe the methodology employed for our bibliographic analysis, present the main results, discuss the identified research themes, and conclude with a summary and questions for future research.

1. Introduction

Agricultural systems face three key challenges—resource management, production inefficiency, and limited sustainability (Dayıoğlu and Turker, 2021). Smart farming technologies (SFTs) are seen as fundamental tools for addressing these challenges. SFTs are expected to provide new solutions to labour intensive tasks, e.g. with smart and crop-specific harvesting, weeding, irrigation, sowing, and seeding applications. They offer new tools for farmers' knowledge and supply chain management and help farmers to increase production efficiency and quality of the production output by better yield monitoring, crop prediction, crop recommendations and variable rate applications (Narvaez et al., 2017; Carducci et al., 2021; Moysiadis et al., 2021; Sharma et al., 2022). Thus, SFTs are expected to disrupt traditional agriculture (Thomas et al., 2023). But although SFTs are steadily gaining market maturity, little is known about their diffusion and even less about the circumstances that lead to their adoption (Osinga et al., 2022). Recent studies on the adoption of SFTs have been criticized for oversimplifying the adoption process (Giua et al., 2022). Additionally, scholars argue that the principle of adoption itself lacks explanatory power (Glover et al., 2019; Oturakci and Yuregir, 2018).

Previous Systematic Literature Reviews (SLRs) have mapped the research trajectories of specific agricultural technologies, such as unmanned aerial vehicles (Istiak et al., 2023), internet-of-things technologies (Huo et al., 2024; Farooq et al., 2020; Terence and Purushothaman, 2020) and precision agriculture applications (Iaksch et al., 2020, Bhakta et al., 2019). These SLRs provide a detailed overview of the state-of-the-art of certain key technologies but offer limited insights into remaining challenges (Sharma et al., 2022), their practical application and integration. A few SLRs extend beyond the technology-specific focus, but they primarily offer descriptive findings rather than a deeper theoretical understanding. These reviews provide three key insights: (1) among SFTs, autonomous robotic systems, the Internet of Things, and machine learning are the most mature, whereas big data, wireless sensor networks, cyber-physical systems, and digital twins are still in early development (Abbasi et al., 2022); (2) foundational technologies essential for SFT integration in farming systems include communication systems, big data analysis, and wireless sensor networks (El Beheiry and Balog, 2023; Abbasi et al., 2022; Sharma et al., 2022); and (3) key adoption drivers include education, farm size, perceived benefits, and information access, while adoption barriers include aging, financial costs, perceived complexity, and lack of infrastructure (Osrof et al., 2023; Sharma et al., 2022).

Despite these SLRs, the literature on smart farming innovation remains scattered mainly because very different technologies and application fields are addressed simultaneously, and an overall theoretical framing is missing. This study aims to map the state of the art of research on smart farming innovation, focusing on identifying the dominant narratives within this broad body of literature. Therefore, we pose the research question one as follows:

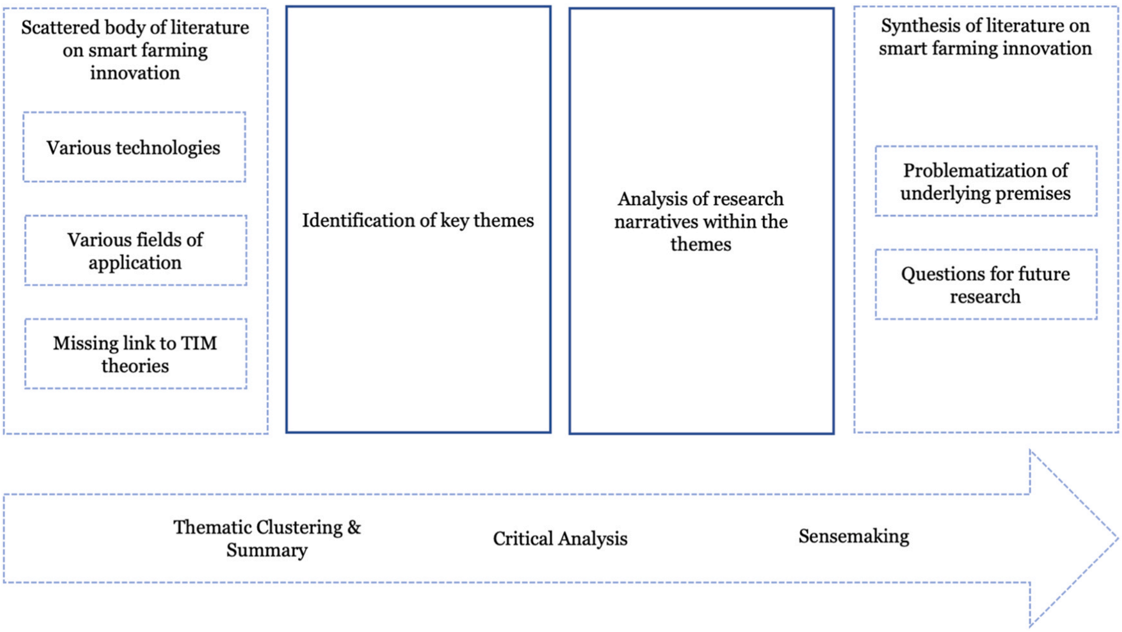

Fig. 1. Research Process.

RQ1. : What are the key themes in smart farming *innovation* research?

Synthesizing existing studies and linking the results back to research and literature is essential for examining an issue or question with a transparent methodology from a new perspective that questions the 'taken for granted' approach. This allows us to critically reflect on dominant framings, assumptions, and knowledge gaps, ultimately leading to better-informed policy design, business strategies, and innovation frameworks (Torraco, 2005).

Our research seeks to follow the idea of integrating a critical analysis by applying a Technology and Innovation Management (TIM) perspective, providing a more nuanced and theory-driven approach to understanding technological change in agriculture. This perspective offers valuable insights by examining the interplay of technological, economic, and institutional factors, thus adding a socio-technical systems level that is needed to comprehensively understand the phenomenon of adaption or non-adaption of smart farming technologies. TIM theories help identify barriers and enablers of adoption, explain market dynamics, and highlight the role of policies, investment, and user behavior in shaping agricultural transformation. Understanding these dynamics is crucial for designing policies, business models, and strategies that ensure scalable, inclusive, and sustainable agricultural innovation. Thus, we revive the TIM concept of technological change as an anchor point to investigate the current discourse on SFTs and pose the second research question:

RQ2. : What are the dominant research narratives within the key themes in smart farming *innovation* research?

To answer these two research questions, we comprehensively review and synthesize existing research at the intersection of smart farming technologies and the TIM domain, using bibliographic coupling to identify prominent research themes, highlight currently prevalent research narratives, and generate questions for future research (for a process overview see Fig. 1). To counter common shortcomings of systematic literature reviews in general (Alvesson and Sandberg, 2020) and trending automated literature reviews (Farhat et al., 2023), we supplement our analysis with an extensive explorative-qualitative discussion of the results, linking our findings back to theory and deriving a comprehensive set of theory-driven research questions for future research. We apply Bruun and Hukkinen's (2003) "Integrative Framework for Studying Technological Change" to guide our discussion and expand our critical review.

Thus, we make three main contributions. First, we give a curated and comprehensive overview of articles on SFTs and innovation to identify key themes and the dominant research narratives within. Second, we enrich the TIM literature by applying three established theories of technological change in a particular sector, making the connection between a specific domain of technological application (SFT) and established theories in the technology and innovation management field. Third, by applying the three theories to challenge the current narratives, we reveal dominant ontological premises in current research that oversimplify technological change. This approach opposes a technology-deterministic and simplistic view of technological developments by integrating a socio-technical systems perspective. This integrative perspective helps us to identify previously unexplored issues and research gaps that would have been overlooked otherwise.

The article is structured as follows: we introduce the theoretical framework, describe the methodology employed for our bibliographic analysis and its discussion. Then we present a descriptive analysis of the data set, presenting the identified research themes. We then discuss each theme and offer theory-driven questions for future research. We conclude with a summary highlighting our main findings and their implications for theory and practice

2. Theoretical background – conceptualizing technological change

Technological change is not merely a linear process but a complex socio-economic and environmental phenomenon (Galtung, 1979; Rosenberg, 1972). As such, technological change implies that new technologies do not only change the economy, politics, and society but are equally shaped by markets, political regulations, and, intentionally as well as accidentally, individual and social groups. This perspective on technological change applies systems thinking by acknowledging that there are feedback loops between the elements or phases of a system, which lead to iterations. Here, following Meadows (2009, p.2), systems are defined as a set of

Table 1

"Commonalities and Complementarities among Three Approaches to Technical Change: Evolutionary Economics (EE), Social Construction of Technology (SCOT) and Actor-Network Theory (ANT)." Source: Bruun and Hukkinen (2003, p. 108).

	Evolutionary Economics (EE)	Social Construction of Technology (SCOT)	Actor-Network Theory (ANT)
What changes?	FROM DIVERGENT TO CONVERGENT ORIENTATION OF ACTION AND INTERPRETATION: – *emergence of technological paradigm after socio-technical lock-in*	– *stabilization of artefact after closure of controversy*	– *creation of network after successful translation of actors and entities*
What is the driver of change?	SOCIALLY ROOTED AGENCY – *organizations promoting different kinds of behaviour*	– *social groups with different interpretations of artefact*	AGENCY ROOTED IN HETEROGENEOUS ENABLING NETWORK OF HUMAN AND NON-HUMAN ELEMENTS
What is the process of change?	ORGANIZATIONAL AND COGNITIVE LEARNING	SOCIAL INTERACTION: – *settling controversies in negotiation*	– *contest of translations*
What delimits change?	CONTEXTUAL STABILITIES: – *institutional rules and routines*	– *technological frame*	CONTINGENCIES IN NETWORKS

"things—people, cells, molecules, [technologies, routines, machines, workers]—inter-connected in such a way that they produce their own pattern of behaviour". Over time, systems develop distinct behavioral patterns, making it logical to view them as whole units rather than analyzing individual parts in isolation. Systems thinking aims to identify and comprehend these patterns, relationships, and functions to guide systems toward desirable outcomes (Sheikheldin and Hambly, 2024). Understanding this reciprocal relationship helps researchers and organizations to understand and anticipate trajectories of technologies, herewith providing guidance for development, market introduction, and regulation (Coccia and Watts, 2020).

Technological change, especially from a systems perspective, is studied by economists and sociologists alike. But most scholars consider the different approaches conflicting (Rip and Kemp, 1998). This view is criticized by Bruun and Hukkinen – "Considering the complexity of technological change – and thus the likelihood that there are no simple explanations to be found – we feel that the exclusive either–or approach is a poor strategy." (2003, p.96). In this article, we follow Bruun and Hukkinen's (2003) suggestion for combining relevant theories on technological challenge current research narratives, identify unexplored issues and thus open up avenues for future research.

In their framework (Table 1), Bruun and Hukkinen (2003) outline the commonalities, differences in terminology and complementarities of three theories: evolutionary economics (EE), social construction of technology (SCOT) and actor-network theory (ANT). They use capitalized statements to indicate commonalities between approaches and italicized statements to specify differences in terminology within a common approach.

In this article, we shift the focus away from comparison and explore the use of this combination of multiple TIM lenses to enhance our analysis of technological change.

What changes? Each theory defines technological change differently. Evolutionary economics (EE) views change as the emergence of new dominant technologies after older systems become entrenched, while social construction of technology (SCOT) sees change as the stabilization of technology after resolving debates among different social groups. In actor-network theory (ANT) it is emphasized that technologies stabilize whenever there is a formation of networks in which humans and non-humans work together effectively. **What is the process of change?** Also, each theory explains the process of technological change differently. EE suggests that change occurs through learning and gradual adaptation within organizations. SCOT describes it as a process of negotiation, where different perspectives are debated and eventually resolved. ANT sees change as a continuous process of interaction and adaptation within

Table 2
Data collection and bibliometric analysis.

Steps	*Research decisions*	*Outcomes*
Step 1: Data collection	Database: SCOPUS Search string: TITLE-ABS-KEY – *"smart farming" OR* – *"precision farming" OR* – *"digital agriculture" OR* – *"ag tech" OR* – *"precision agriculture"* *AND* *adoption OR* *diffusion OR* *"technological change" OR* *"innovation management"*	**Identified** articles n = 1784
Step 2: Identification of relevant articles	Exclusion criteria: – Another language than English – Not peer-reviewed – No abstract	**Excluded** articles n = 811 **Included** articles n = 973 No. of cited references = 48,506
Step 3: Clustering 3.1 Bibliographic coupling	Level of analysis: document Citations per document: 5 Clustering: fractional counting	**Clustered** articles n = 560
3.2 Building meaningful clusters	Normalization: association strength Min. cluster size: 10, merge small clusters Resolution: 1.0	**Clustered** articles n = 523
3.3 Layout	Attraction: 2 Repulsion: 0	Reducing barely related clusters
3.4 Visualization	Weights: total link strength Min. link strength: 1.00	Better visibility of links between clusters
Step 4: Analyzing the clusters 4.1 Keyword co-occurrence analysis	– Association strength algorithm – Biblioshiny automatic layout algorithm – Louvain clustering algorithm	Computer-supported analysis of the key themes of the clusters
4.2 Qualitative Analysis	Additional Narrative review	Identification of important publications within the clusters and enrichment of co-occurrence analysis through narrative review

evolving networks. **What drives and limits change?** The drivers of technological change vary across the three theories as well. EE attributes change to organizations that foster innovation and promote new ways of doing things. SCOT highlights the role of different social groups who shape technology through their interpretations and debates. ANT argues that change is driven by relationships between human and non-human actors, where their interactions determine the development of technology. Finally, each theory identifies different constraints on technological change. EE argues that change is restricted by institutional rules and established routines. SCOT points to the limitations imposed by existing technological frameworks and infrastructures. ANT suggests that change is constrained by the dynamic nature of networks, where shifts in relationships can either enable or hinder technological development.

3. Method

We conducted a systematic literature review (SLR) to provide a comprehensive overview of seemingly unrelated fields of technology and innovation management and smart farming technologies. SLRs are valued in the research community for their replicable, scientific, and transparent protocol. While traditional narrative reviews are less formalized and thus more flexible, they usually rely on fewer articles (Rousseau et al., 2008) and tend to lack transparency and reproducibility (Wilden et al., 2019). Following a SLR allows us to address the inherent bias associated with traditional reviews as the selection of the analyzed studies is not based on the assumptions and perspectives of the researchers (Ramos-Rodríguez and Ruíz-Navarro, 2004; Tranfield et al., 2003), leading to high inclusiveness of the dataset.

To derive key themes of current literature in smart farming innovation research (RQ1), we chose a bibliometric approach. Bibliometric analysis is the statistical analysis of a scholarly communication network. This approach enabled us to facilitate an objective analysis of a large body of extant research spanning over two decades. It is known for its potential to reveal a scientific research's structural and dynamic aspects (Casadei et al., 2023; Cheng et al., 2023; Barata, 2021; Börner et al., 2003). To deepen our understanding of the clusters, we added a keyword co-occurrence analysis for each identified cluster. Building on this, we derived a narrative for each cluster, which we then enriched through a manual, qualitative analysis of the most prominent articles within each cluster. Table 2 provides an overview of the data collection and analysis process of the clusters.

A common shortcoming of systematic literature reviews is an overly strong focus on extensively describing prior research without challenging the underlying theoretical foundations, thereby omitting the opportunity to pave the way for theoretical advancement and new perspectives. To overcome this weakness, we supplement our analysis with an explorative-qualitative discussion of each research theme through three TIM lenses: evolutionary economics (EE), social construction of technology (SCOT) and actor-network theory (ANT). By doing so, we aim to challenge the most dominant research narratives (RQ2) to open up avenues for future research in smart farming innovation research.

3.1. Data

We used the SCOPUS database for our analysis. SCOPUS is well known for its high-quality data and rigorous content selection (De Marchi et al., 2020) and is thus one of the leading databases used for scientific work (Baas *et al.,* 2020). We focused our search on articles that concern smart farming technologies but also touched the TIM domain (see Table 2). Therefore, we searched for publications through a Boolean search by running the following query:

> *TITLE-ABS-KEY ("smart farming" OR "precision farming" OR "digital agriculture" OR "ag tech" OR "precision agriculture") AND (adoption OR diffusion OR "technological change" OR "innovation management")*

We restricted our search to peer-reviewed academic articles published in journals known to the SCOPUS database. We only included articles in English and excluded articles with missing abstracts, as we used the abstract to interpret the results of our bibliographic coupling analysis with a keyword co-occurrence analysis. This resulted in 973 included articles and 48,506 cited references.

3.2. Data analysis

We use bibliographic coupling (Kessler, 1963) to map the knowledge structure of the literature and identify different research clusters within our field of inquiry. Our level of analysis was the document, and we clustered publications on the assumption that publications that cite the same references are related to each other based on intellectual proximity (Perianes-Rodriguez et al., 2016). As such, the number of shared cited references measures the level of relatedness of the two publications. We assume that publications appearing together in a cluster share a common perspective and are built upon a similar intellectual base (Nájera-Sánchez et al., 2020). We used VOSviewer (version 1.6.17) to create our publication network. Following Perianes-Rodriques et al. (2016), we applied an initial threshold of at least two citations for each document to exclude publications without bibliographic coupling links from our dataset. With a minimum of two citations, 728 out of the 973 publications met the threshold. This, however, led to unmeaningful clusters. We then used an iterative approach and adjusted the threshold of minimum citations until we received clearer patterns within the clustering, resulting in a threshold of at least five citations per document. Ultimately, we included 560 out of 973 publications in our bibliographic coupling analysis. We applied the fractional counting approach as implemented in VOSviewer to cluster the publications. We chose the fractional counting approach for our analysis because we assume that all the publications within a cluster are equally representative of the cluster's topic (Pitt et al., 2021; Perianes-Rodriguez et al., 2016). For each of the 560 documents, the bibliographic coupling links' total strength with other documents was calculated. We found several small and poorly connected clusters. Therefore, we adjusted the minimum total strength of bibliographic coupling links until a network emerged, which we consider representative of our field of inquiry. This network considers 523 documents with the highest total bibliographic coupling strength, whereby a strong bibliographic connection implies conceptual similarity. Next, we parametrized the layout, clustering, and normalization algorithms in VOSviewer: We used the association strength method for normalization. This method is set to default by VOSviewer and is strongly supported by van Eck and Waltman (2009). Afterward, we exchanged some default values (see Table 1) to better display the links between the clusters and reduce the amount of barely related clusters to receive more meaningful results.

We used a text-mining approach to create preliminary analytical clues for each cluster by analysing the keyword co-occurrence for each identified cluster and creating a conceptual structure map. We chose this mixed-method approach of bibliographic coupling, keyword co-occurrence analysis and a qualitative analysis because it enabled us to comprehensively understand each cluster's intellectual base and conceptual structure while processing a large number of publications (Casadei et al., 2023; Pitt et al., 2021). For the keyword co-occurrence analysis we used Biblioshiny, a non-coders application of the bibliometrix R-package. For the parametrization, we followed a conservative approach and used the association strength algorithm for normalization (van Eck and Waltman, 2009), the automatic layout algorithm, which is supposed to choose the best layout in terms of graph readability automatically, and the Louvain clustering algorithm (Lancichinetti and Fortunato, 2009). We then analysed the derived keywords and its structure with a multiple correspondence analysis to map the conceptual structure of each cluster, which we present in a conceptual structure map (De Martino et al., 2025; Bulut and Yıldız, 2024). Conceptual structure maps are well suited to map the intellectual structure of a research field, e.g. to highlight its most relevant topics (Aria and Cuccurullo, 2017). Building up on this, we enriched the analysis through qualitative insights to identify common ground in the clusters. Thus, we highlight the three most outstanding research themes.

3.3. Explorative-qualitative discussion of the themes through a TIM lens

Systematic literature reviews are often criticized for focusing too much on existing research and thus falling short on providing new perspectives. To encounter this, we added an additional step of analysis to our SLR.

After deriving three distinct research themes and supplementing them with a narrative analysis, we finally discuss them in the light of the three prominent TIM theories: EE, SCOT and ANT. This combination of perspectives is in line with Bruun & Hukkinen's "Integrative Framework" (2003). Here, the term 'integrated' does not imply the merging of evolutionary economics (EE), social construction of technology (SCOT) and actor-network theory (ANT) into a new theory. Rather, it means that challenging our research topic through the lens of all three theories enables us to gain a comprehensive understanding of the following questions on technological change: What changes? What is the process of change? What drives and limits change? This integrative approach allows us to identify previously unexplored issues and research gaps that would have been overlooked otherwise.

4. Results

4.1. Descriptive analysis

Fig. 1 displays the annual scientific production of innovation research on smart farming technologies, showing how innovation research-specific topics have accompanied the development of digital agriculture since the origins of precision agriculture. During the

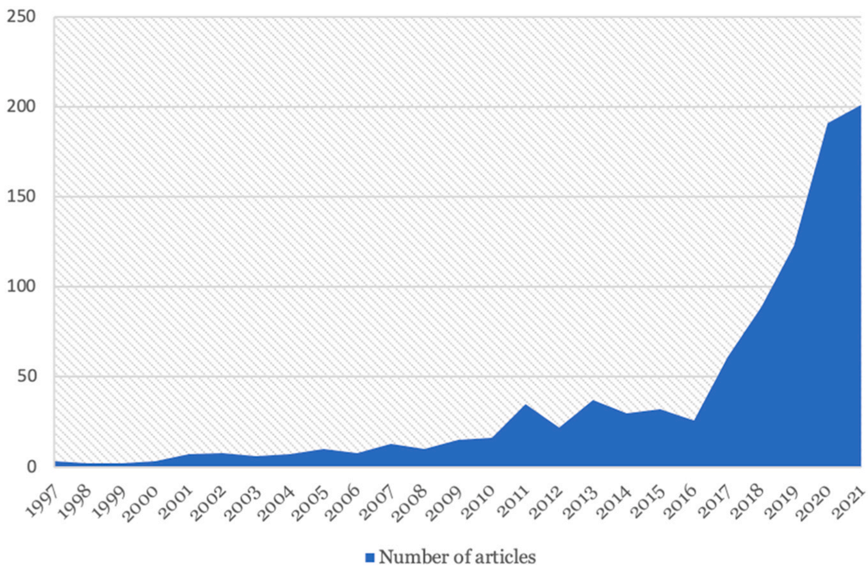

Fig. 2. Annual scientific publications of innovation research on smart farming technologies.

initial years of precision agriculture, less than 15 articles were published per year on SCOPUS. This publication volume exceeded for the first time in 2010 (16 annual published articles) and doubled in the following period to approximately 30 annual publications between 2011 and 2016. This was followed by a period of acceleration: in 2017, the annual scientific production doubled again (61 annual published articles). In 2019 it was at 123 articles per year and rose to over 200 articles in 2021, demonstrating an exponential interest in this research field.

The analyzed articles reveal a significant concentration of research output in Australia, which leads the dataset with 351 articles. Brazil follows with 95 articles, while China ranks third with 56 articles. The map further highlights strong research contributions from European countries such as Switzerland, Austria, and Germany, alongside North American nations like the United States and Canada. This distribution suggests a regional focus on the subject matter, with Australia emerging as a dominant hub of scholarly activity.

We extracted the top 10 journals that have published articles on SFT innovation, which together account for 33.3 % of the total dataset (Table 3). This indicates that the leading journals for covering technology development and application in agriculture are most relevant for the SFT innovation field so far.

Although all identified articles relevant to this SLR deal with innovation, only a small proportion of publications come from journals associated with the TIM disciplines. Additionally, we mapped the journals in which the articles were published to subject areas, thereby extending the analysis beyond the top 10 publication sources (Fig. 3).

From this mapping, a similar picture emerges – in the context of smart farming, there is a separation of innovation from technology research. This highlights the importance of bridging the TIM and the technology perspective to encompass technological change in its entirety.

4.2. Bibliographic coupling: most prominent research themes

Overall, we found the 523 included articles within this research stream to be grouped into twelve clusters, represented in Fig. 4. A complete list of the analyzed articles and clusters can be found in Appendix II. The size of the nodes represents the total link strength of an article, that is, the total strength of the links of a given article with other articles. The distance of the nodes reflects the strength of the relation between two items (van Eck and Waltman, 2010). The closer they are, the more we assume they have in common. We observe a lively exchange of ideas among the clusters within the literature corpus. Amongst the twelve clusters, we identify three prominent research themes.

The first research theme (A) centers on technological improvements aimed at enhancing the efficiency and profitability of farming practices. The red and blue clusters emphasize soil and water management, crop monitoring, and the integration of precision agriculture tools like GIS, remote sensing, and UAVs, with a focus on maximizing yield and economic returns. Smaller clusters explore specialized applications, such as disease management, eco-farming, and precision pesticide use, highlighting sustainability-aimed approaches. Research theme B centers on the adoption and integration of smart farming technologies (SFTs), focusing on the social, economic, and psychological factors that influence farmers' decisions. Research theme C includes studies that examine ethical, political, and social implications of SFT adoption.

In the following section, we outline the narrative of each research theme in detail. Therefore, we present the results from the keyword co-occurrence analysis per cluster in a conceptual structure map. We used the prominent identified keywords as a starting point for outlining the content of each cluster, and enriched these findings by a more detailed qualitative reading. The results from this qualitative analysis are presented following the conceptual structure map. The description of the narrative of each research theme is followed by a discussion in the light of the three TIM theories. By detailing the extent to which the three theories – EE, SCOT, and ANT, help us understand the existing literature and discussing it in its entire complexity, we have identified several blind spots of current research. Highlighting them does not reduce complexity and uncertainty at first sight, but it helps scholars to grasp and address those open issues systematically. As a result, scholars can learn to ask the right questions and better examine the underlying processes of technological change. Consequently, we conclude the discussions by proposing questions for future research. The exemplary research questions are provided in a table following the description and discussion of each theme. They are not intended to be exhaustive, but to serve as a starting point for future research.

Table 3
Top 10 journals by numbers of articles from our data set.

Journal	*Number of Articles*
Computers and Electronics in Agriculture	87
Precision Agriculture	77
Remote Sensing	29
Sustainability (Switzerland)	27
Agronomy	23
Journal of Rural Studies	22
Agricultural Systems	20
Sensors (Switzerland)	14
Agriculture (Switzerland)	14
Applied Engineering in Agriculture	11

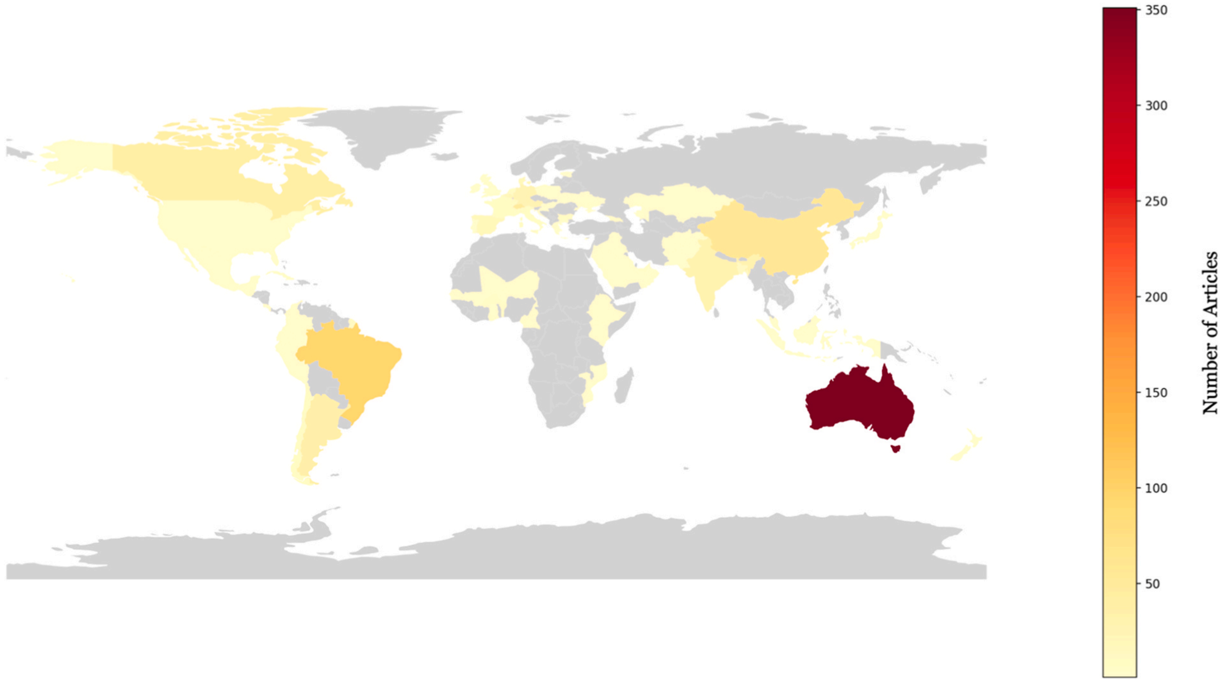

Fig. 3. Distribution of articles by country and number of articles.

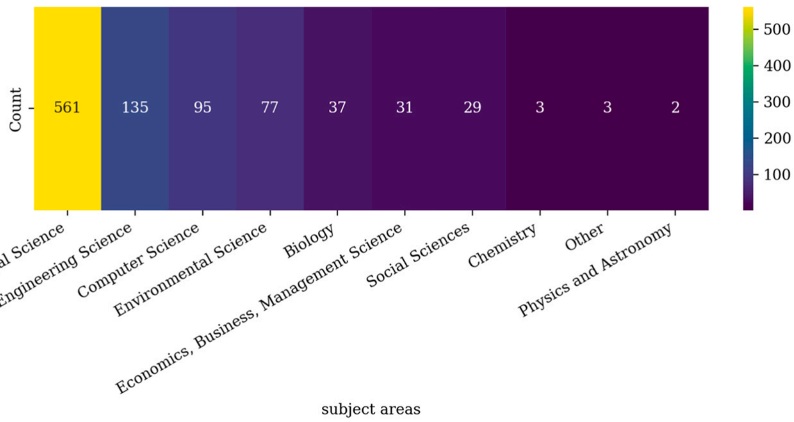

Fig. 4. Article count per subject area.

4.2.1. *Research Theme A: SFT diffusion – a technocentric perspective*

The articles in the red cluster (Fig. 4, Cluster 1) are primarily concerned with improving and adapting smart farming technologies to different field conditions to improve plant quality, enhance yield, and increase profitability.

The articles in this cluster are divided into two distinct sub-clusters (Fig. 5). The upper subcluster is related to water management, as suggested by terms like “irrigation”, “water supply” and “soil moisture”. The lower subcluster contains terms related to soil and yield. Terms like “electrical conductivity” and “electric conductivity”, “soil chemistry”, “soil fertility”, and “soil organic matter” suggest an interest in soil health assessment. “Kriging”, “remote sensing” and “GIS” indicate the use of spatial and mapping technologies to analyze soil variability and optimize land use. These techniques help in site-specific soil management, which are expected to lead to better decision-making here. Terms like “crop yield”, “yield response”, “crop production” and “productivity” are directly related to how well crops perform under different soil conditions. Precision agriculture techniques such as “NDVI” (Normalized Difference Vegetation Index), “software” and “agricultural machinery” are expected to help improve crop monitoring and maximize production. The keyword “cost-benefit analysis” appears in this context with keywords like “economic analysis”, “profitability” and “technology adoption”. This reflects concerns about the return on investment for farmers. Thus, the link between productivity and other economic terms suggests that researchers are evaluating how better soil and crop management, as well as data-driven decision making, translate into higher profits.

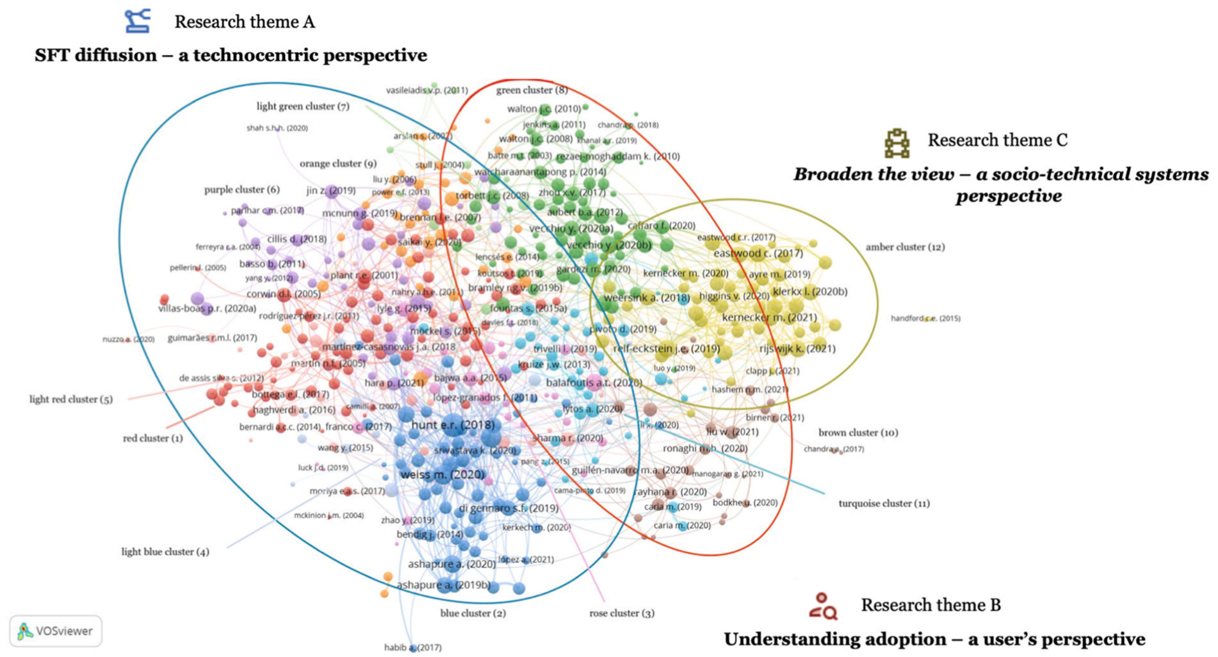

Fig. 5. Bibliographic coupling network: structure of TIM research on SFTs. Source: Created by authors via VOSviewer.

Many studies in this cluster are concerned with creating new technological knowledge. The authors of these studies aim to increase the value of technologies by improving the support of farming activities through better technological features, e.g., through research on how to improve field mapping in terms of spatial and temporal factors, how to (mathematically) handle variabilities, e.g., within a field, and how technology can support cultivation techniques with precision agriculture. Within this cluster, we also observe knowledge generation not by studying the respective technologies directly but through literature reviews about the state of the art of certain technologies and advancements in precision agriculture. Overall, the articles in this cluster seek to improve SFTs from a

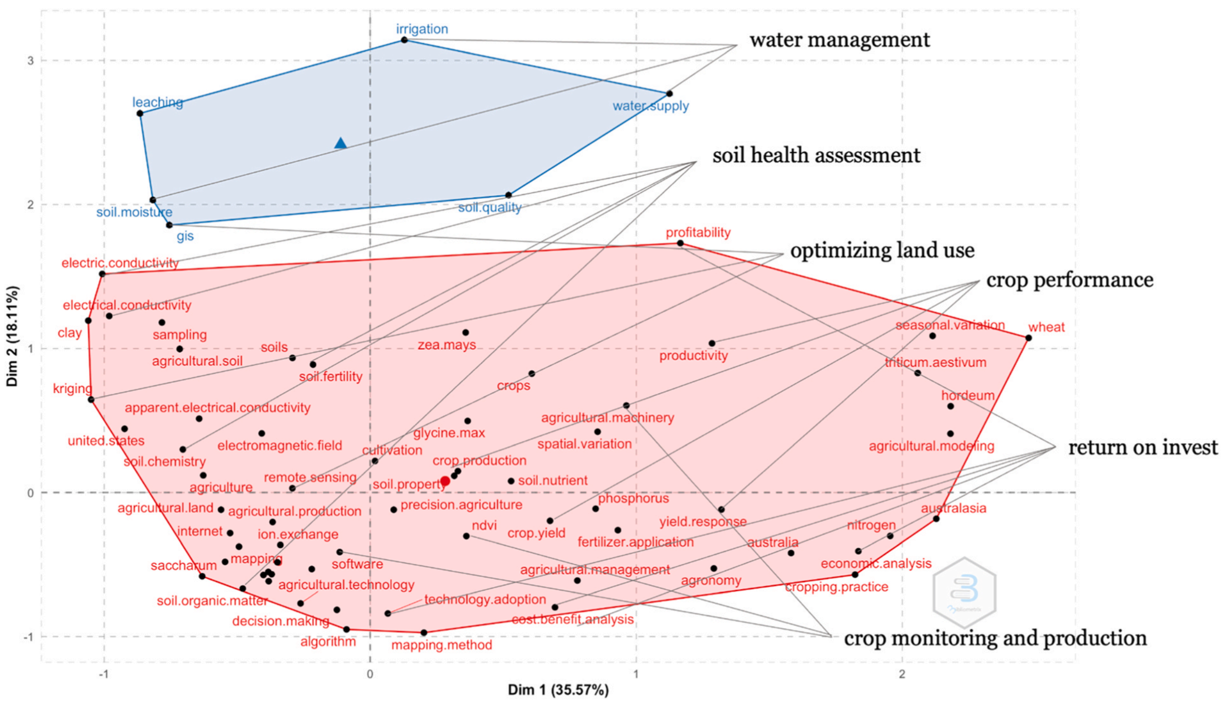

Fig. 6. Factorial map of cluster 1. Source: Created by authors using Biblioshiny.

technological perspective. One of the main research topics in this cluster is the profitability of SFTs (Viscarra Rossel et al., 2001), while increased profitability is consistently associated with higher adoption rates and wider diffusion of SFTs (Sanches et al., 2019).

Additionally, we found articles concerned with better technology design, e.g.:

> *"In precision agriculture there is often a large knowledge gap between developers and users, […]. By paying attention to developing of protocols and realistic performance criteria, developers can exert a stronger, positive influence on the rate and breadth of adoption." (Lamb et al., 2008, p. 4)*

A key part of the blue cluster (Fig. 4, Cluster 2) is focused on unmanned aerial vehicles and other remote sensing applications. In the first subcluster of the blue cluster (Fig. 6) we find articles concerned with crop monitoring (upper cluster), connected through keywords like "landsat", "satellite imagery" (satellite-based monitoring) with the keywords "mapping" and "information management". The second subcluster (lower cluster) highlights an interest in cutting-edge precision agriculture technologies like sensor-based imaging ("multispectral sensors", "remote sensing system" and "spectral analysis"), unmanned vehicles like drones ("unmanned aerial systems", "unmanned aerial vehicles") and robots ("agricultural robots", "unmanned vehicles") and machine learning technologies ("artificial intelligence", "machine learning", "deep learning").

Those technologies are being studied for improved cost effectiveness ("cost effectiveness", "mean square error", "costs"). Most of the studies are concerned with the application of these technologies in contexts of uneven terrain, e.g., vineyards or forests, but a smaller amount of studies also studies the application for other crops. The scholars' underlying premises here are similar to those in the red cluster: It is expected that improvements in technology will lead to increasing diffusion.

The rose (3), light blue (4) and light red (5) cluster articles (Fig. 4) study how SFTs can address different agricultural conditions. The articles in the rose cluster, for example, primarily address plant diseases through the use of robotic and heavy machinery technologies (Fig. 7, No 3). Meanwhile, articles in the light blue (4) cluster relate primarily to soil conditions (Fig. 7, No 4), and the articles in the light red (5) cluster focus on water management in particular (Fig. 7, No 5). These clusters are rather small and consider niche topics. The articles in the purple (6) and light green (7) cluster (Fig. 4) explore a wide range of technologies to improve soil quality and plant health. Articles in cluster 6 deal with these issues by research on techniques for precision pesticide application (Fig. 7, No 6), while the articles in cluster 7 investigate these issues from a perspective of alternative, often more ecological, approaches to farming (Fig. 7, No 7). Other than the clusters discussed before, the articles in these two clusters tend to reflect on the broader environmental impact of the technologies. Overall, in this first research theme, scholars seek to solve particular problems through technology improvements.

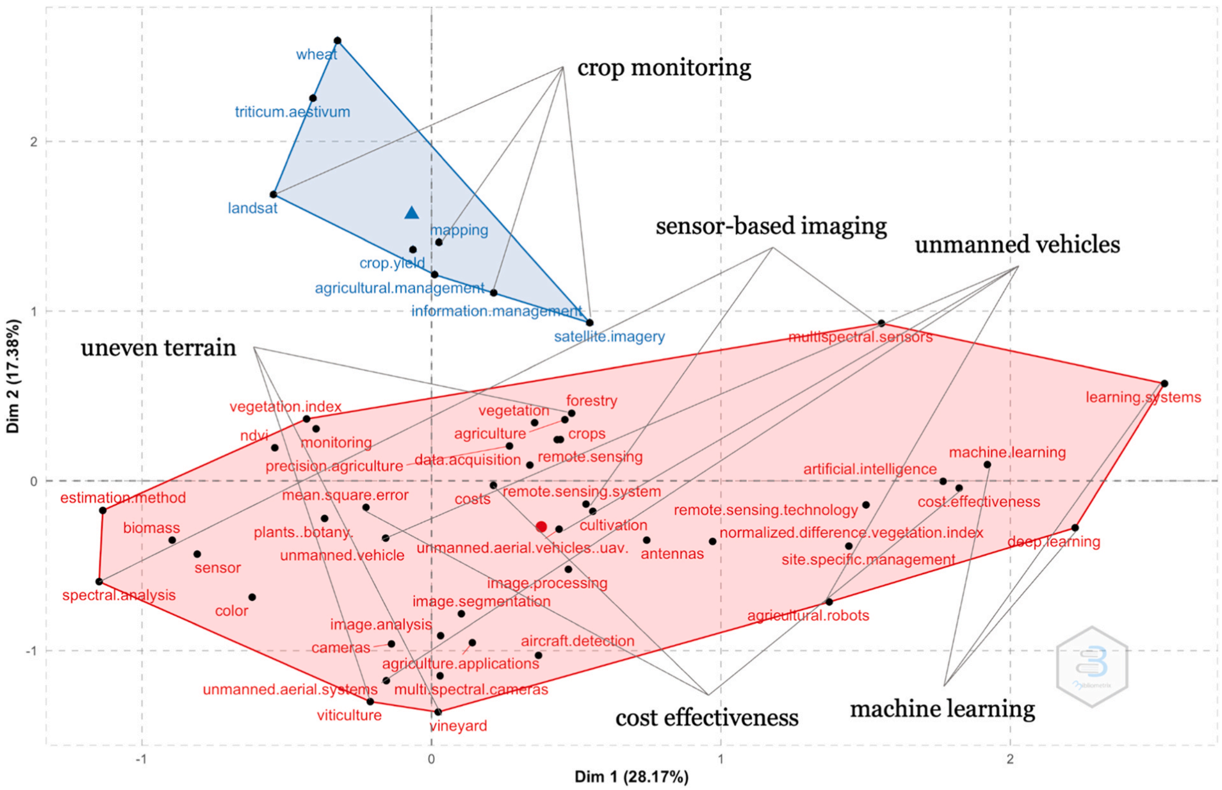

Fig. 7. Factorial map of cluster 2. Source: Created by authors using Biblioshiny.

4.2.2. Interpretation of Research Theme A through the integrative framework

Within this research theme, the studies focusing on improving the technological features of SFT have two different missions: firstly, the more general adaptation of SFT to established farming practices. Secondly, the more specific adaptation of SFT to biosecurity, e.g., certain plant needs, local (soil) conditions, and more specific problems such as a pest infestation that often occurs in a certain plant species. In this research theme, we find an interesting research narrative guiding the studies: an expected linear causality between technological functionality, financial reward, and technology adoption. The underlying assumption is that the better the technology is adapted to the requirements of the farming environment, the more profitable it is and the more likely it is to be adopted. Our interpretation of the common narrative in the clusters assigned to theme A is that technological improvement will change diffusion rates.

Taking an **EE** perspective, it becomes apparent that the criteria for evaluating new technologies are firmly embedded in the current agricultural system. In EE terms, the process of selection and variation of smart farming technologies takes place within the boundaries and rules of the established agricultural system, while the unit of analysis is the technology (Mokyr, 2000). However, there is often much uncertainty surrounding the form and function of new technologies as they emerge. Social groups differ in their definition of a problem and their interpretation of a new technology (Geels, 2020). Using the **SCOT** lens for research theme A, we can reflect on the different phases of technological change in more detail. It is important to better understand how technologies will affect established farms' routines and processes, as this will highly influence the users' interpretation and usage of new technologies. SCOT highlights the fact that technology is not a neutral tool but rather is shaped by the social, cultural, and political context in which it is developed and used. Another key element in SCOT is the effect of *closure*. *Closure* occurs when different actors who favor different technological approaches find a compromise. When we look at our research theme A, it becomes apparent that scholars still synthesize the literature for different technological approaches. In "technology management terms," one could say that there is no *dominant design* for SFTs yet. This is interesting in that a lack of a dominant design might be a factor that explains slow diffusion (Utterback, 1994). Within Research Cluster A, we observe that the discussions around evolving technology features exclude the users' perspective in the developing phase of the technology. Users are, in the articles of these clusters, only included in the introduction phase of the new technologies. Hence, from a SCOT perspective, we argue that including users in the development phase early on not only ensures that new technologies are developed and adopted in ways that are responsive to the needs and preferences of different social groups but also that they succeed in the market.

ANT also emphasizes the relationships between human and non-human actors in the creation, implementation, and diffusion of innovations. Involving users would offer novel perspectives in that ANT could be used to analyze the extent to which power structures between machine manufacturers and farmers are already embedded in the design of a technology and the emerging dominant design.

While our findings criticize the underlying assumption of a causality between improved functionality and diffusion rates, this also highlights avenues for future research. We have outlined the need to further investigate how SFTs are embedded in organization structures and the broader agricultural system, how they interact with users in different phases of the development and application, and with the broader ecosystem, e.g., of machine suppliers, input suppliers and regulators. To guide future research, in the following we present a set of theory-driven research questions (Table 4) outlining potential directions that can build upon our findings and address existing gaps in the literature.

4.2.3. Research Theme B: understanding adoption – a user's perspective

In research theme B, the adoption of SFTs is explored from different angles and with different methodologies. In the green (8) cluster (Fig. 4) the keywords are centered around the terms "adoption" and "technology adoption" (Fig. 8, No 8) which suggests that the articles in this cluster examine factors that drive the adoption of different SFTs (e.g., "precision agriculture technology", "precision farming", "web services", "artificial intelligence", "decision support systems"). From the keyword co-occurrence analysis, factors like "education", "perception", "farmers' knowledge", "policy making", "farm size", "finance" can be highlighted. The focus of the orange (9) clusters (Fig. 4) is on SFTs ("precision agriculture", "remote sensing", "GPS", "GIS", "agricultural robots", "sensors") for improving

Table 4
Suggested research questions for future research in research theme A.

Evolutionary Economics (EE)	*Social Construction of Technology (SCOT)*	*Actor-Network-Theory (ANT)*
Research Theme A: SFT diffusion – a technocentric perspective		
– What are the challenges and opportunities associated with integrating smart farming technologies into traditional farming systems, and how can these challenges be addressed through innovative business models and partnerships? – What criteria are used to evaluate the profitability of new smart farming technologies, and how do these criteria reflect the envisioned sustainability change in the agricultural system? – How do smart farming technologies impact the evolution of the agricultural industry in terms of technological innovation, organizational structure, and market dynamics?	– Who are the users of smart farming technologies, and how can their needs be addressed early on in the development process of new smart farming technologies? – What is the role of engineering research communities in directing smart farming technologies before they enter the market? – How do new farming technologies impact established routines and processes on farms, and how does this influence users' interpretation and usage of the technologies?	– Which power structures between machine suppliers and farmers become (in)visible through smart farming technologies? – How do smart farming technologies mediate the relationships and interactions between different actors within the agricultural sector, such as farmers, input suppliers, buyers, and regulators? – How do farmers translate smart farming technologies and thus shape the direction of technology development through their interactions?

economic returns and efficiency (“economic analysis”, “cost-benefit analysis”, “agricultural analysis”).

In research theme B, a diverse set of methodological approaches is applied. Scholars use mathematical modeling of user decisions (e.g., Batte, 2005; D’Antoni et al., 2012), qualitative interview studies (Busse et al., 2014, Kenny, 2011) and mixed-method approaches (e.g., Alvarez and Nuthall, 2006; Bellotti and Rochecouste, 2014). These articles share the interest in farmers’ needs, their perceptions of technology, and why they tend to adopt or not adopt SFT. In most of the articles, we find an optimistic stand on technology adoption, whereas Massey et al. (2008) explicitly report that farmers are highly doubtful about the usefulness of the technology:

> *“For over a decade, farmers have been collecting site-specific yield data. Many have formed doubts about this investment because of their inability to directly apply this information as feedback for improving management.“ (*Massey et al., 2008*, p.52)*

Overall, these studies review how user groups interpret certain technologies and try to find technical solutions that would lead to stronger adoption behavior, e.g.:

> *“The surveys have shown that farmers are in general optimistic about the future prospects for Precision Farming in Denmark. Nonetheless, compatibility between hardware and software, as well as lack of serviceability is for many farmers a serious impediment to adoption.“ (*Pedersen et al., 2004*, p. 7)*

Articles in the brown (10) and turquoise cluster (11) are specifically concerned with farmers’ usage of big data technologies (Fig. 8, No 10 and 11) like “internet of things”, “wireless sensor networks” and “management information systems”. blockchain, information, and communication technologies, wireless sensors, and integrated smart farming systems solutions (Fig. 8, No 10 and 11).

4.2.4. Interpretation of Research Theme B through the integrative framework

Within research theme B, there is a strong user focus by looking at users’ characteristics in adopting and applying SFTs. The narrative in this research theme is that farmers and farms have certain characteristics that influence whether or not technology adoption occurs. From an **EE** perspective, we add another set of factors to this list: contextual stabilities, like established routines on farms or support services for specific machine brands. Additionally, when we review the literature in this theme through the EE lens, we can highlight that scholars tend not to differentiate between farmers as individuals and as decision-makers of an organization. In the reviewed literature, farmers are frequently portrayed as individuals who resist adopting new technologies due to their individual characteristics (e.g., age, gender, and educational background). EE adds another layer of explanation here by showing that farmers are also leaders of organizations and that research on innovation needs to integrate this. EE also puts the focus on the importance of firms (and, therefore, farms) actively participating in selecting technologies. This is particularly important because most farms face resource constraints and follow fixed trajectories, e.g., integrating new technologies into their workspace setting. This might create a regime that hinders the diffusion of new technologies. By paying attention to farms that actively engage in R&D projects or that are attempting to challenge their routines and practices, scholars can gain a more comprehensive understanding of the actual issues that farmers encounter when adopting new technologies.

SCOT emphasizes the role of different social groups with their interactions and negotiations in shaping the meaning and use of technologies. The articles in research theme B highlight various factors that can either facilitate or hinder the adoption of new

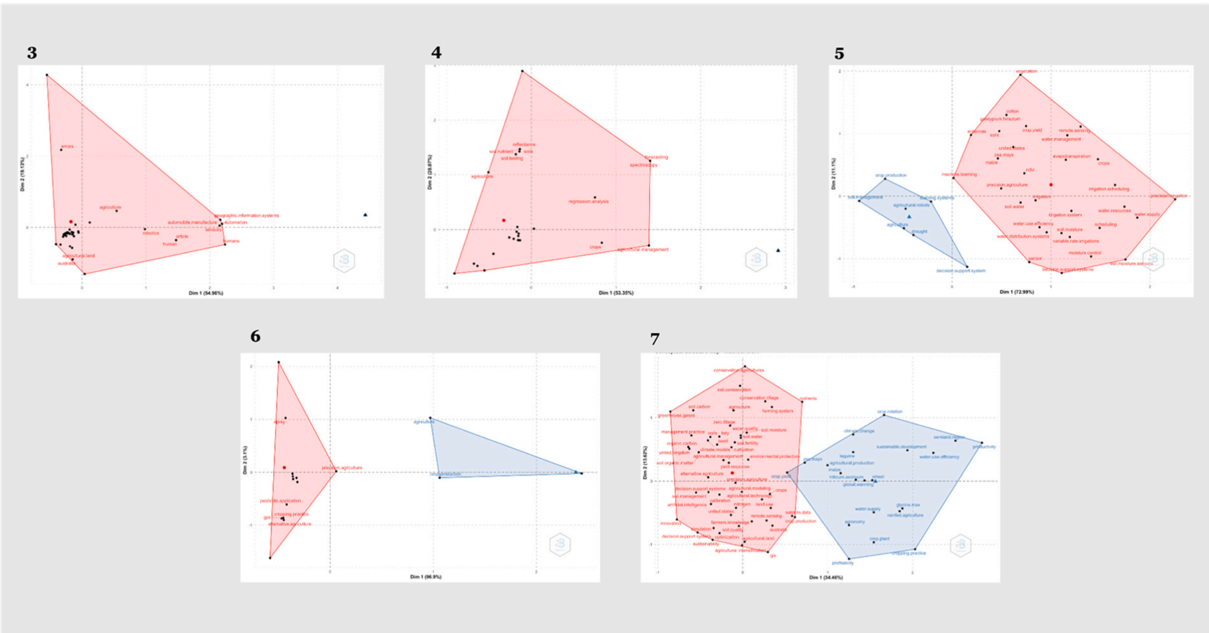

Fig. 8. Factorial map of cluster 3–7. Source: Created by authors using Biblioshiny.

technologies in agriculture. These factors include the expectations and improvements that farmers hope to achieve through technology adoption and the perceived weaknesses of current technological concepts. However, none of these studies have identified a more differentiated typology of different user groups, meaning that controversies between stakeholder groups may become invisible. Nevertheless, a more differentiated typology of users and stakeholders is needed to fully understand the drivers of technological change in agriculture. Additionally, the SCOT perspective highlights that it may be necessary to create new interpretations of technology and develop new technological frames that match the user groups whose problems should be addressed.

In the context of research theme B, scholars discuss how digital technologies like machine learning and artificial intelligence arise as new forms of learning activities that outperform humans' capabilities to learn. As **ANT** attributes agency to non-human, technological artifacts, scholars could shed light on how technological entities intervene and change farmers' decision-making, how they reconfigure current routines and practices, and how collaborative learning between farmers and machines evolves by investigating the learning networks of different actors, including technical entities. Those findings might complement the EE view of organizational learning and agency rooted in organizations and therefore add new perspectives.

While the articles in this research theme have advanced our understanding of the importance of socio-economic factors to technology adoption, research theme B also reveals several areas that warrant further investigation. We suggest the need for a deeper inquiry into organizational constraints to the technology adoption, as well as the exploration of existing technological frames of users and stakeholders. Table 5 outlines theory-driven questions that can guide scholars in expanding upon our findings and advancing the field.

4.2.5. Research Theme C: broaden the view – a socio-technical systems perspective

4.2.5.1. Research theme C consists of only one cluster, which is, therefore, most coherent. Articles in this amber cluster (12) engage with SFTs from a socio-technical systems perspective. The most apparent theme within this cluster is an interest in socio-ethical questions. This is highlighted by central keywords like “ethics”, “humans”, "political economy", "governance approach", “sovereignty” and “rural development”. (Fig. 9). Several scholars discuss the possibility of a digital divide and technological lock-in situations and raise critical awareness on questions around equity, data sovereignty, sustainability and issues of the distribution of labor within digitized production systems (Carolan, 2017, 2020; Eastwood et al., 2019b; Klerkx and Rose, 2020). Governance mechanisms and private-public research partnerships are also critically discussed (Rotz et al., 2019).

> *“These socio-ethical dilemmas included data privacy and power relations between farmers and companies relating to data acquisition and ownership. Changes to the nature of farming and human–animal relations were also identified as socio-ethical dilemmas, potentially leading to farmers and/or society rejecting smart farming technology-based approaches—as noted by Wathes et al. (2008).* “ (Eastwood et al., 2019b*, p. 760)*

Additionally, we find scholars interested in how the adoption of a SFT re-configures current work routines and the farmers' interaction with technologies (Comi, 2020; Higgins et al., 2017).

> *“If I ask ‘who farms?’ the answer is, again, a large, changing constellation of actors as opposed to a human individual.“ (*Comi, 2020*, p. 10)*

The emergence of new knowledge networks (Ayre et al., 2019; Eastwood et al., 2019a) is another research focus within the amber cluster. Especially the role of technology advisors in the process of technological change is highlighted.

4.2.6. Interpretation of Research Theme C through the integrative framework

Research theme C contains articles exploring agricultural innovations from different, often interdisciplinary, directions. Many authors take a systematic perspective or critically reflect on the ongoing change in agriculture. The role of farming advisors and the demand for data analysts is expected to be rapidly changing. As established organizations show a special interest in SFTs, new players, particularly start-ups, are entering the market, and private-public partnerships are emerging. From an **EE** perspective, these developments suggest the need for a better understanding of how this affects the firms' routines and the existing body of knowledge in the industry. We can also expect that firms will develop new business models that better address farmers' needs and make technology

Table 5
Suggested research questions for future research in research theme B.

Evolutionary Economics (EE)	*Social Construction of Technology (SCOT)*	*Actor-Network-Theory (ANT)*
Research Theme B: Understanding adoption – a user's perspective		
– Which resource constraints, such as budget and human resources, impact the adoption of new technologies in agriculture? – How do contextual stabilities, such as established routines and support services, influence farmers' adoption behavior? – What makes farmers actively engage in R&D projects to challenge their existing practices?	– Who are the future users of smart farming technologies, and how do their technological frames differ in different agricultural contexts? – How do interpretations of SFTs evolve in farmers' networks and how do they impact the application of SFTs? – How can new technological frames support farmers' engagement in a sustainability transition in agriculture?	– Which farming routines are impacted by technological entities and how does this change farmers' decision-making? – How do smart farming technologies generate new forms of knowledge and expertise, and how are these distributed across different actors? – How can smart farming technologies influence farmers' agency and identity by shaping their practices, routines, and perceptions?

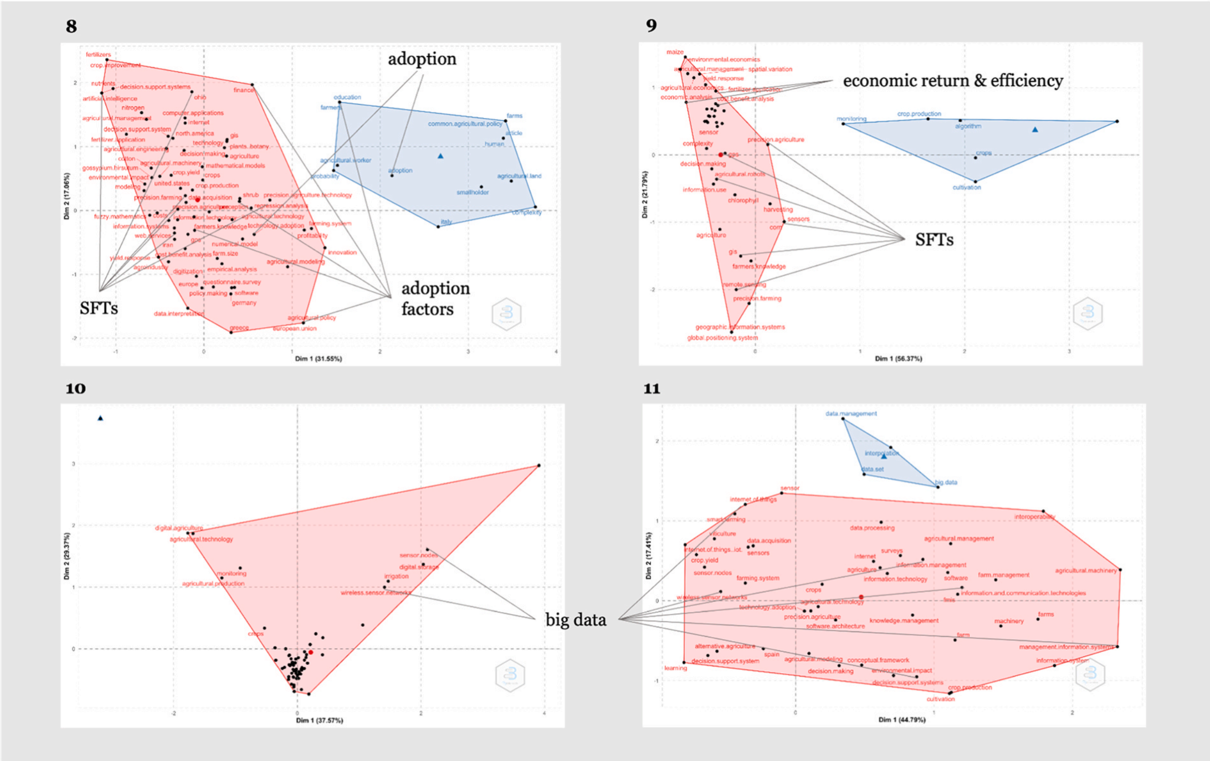

Fig. 9. Factorial map of cluster 8–11. Source: Created by authors using Biblioshiny.

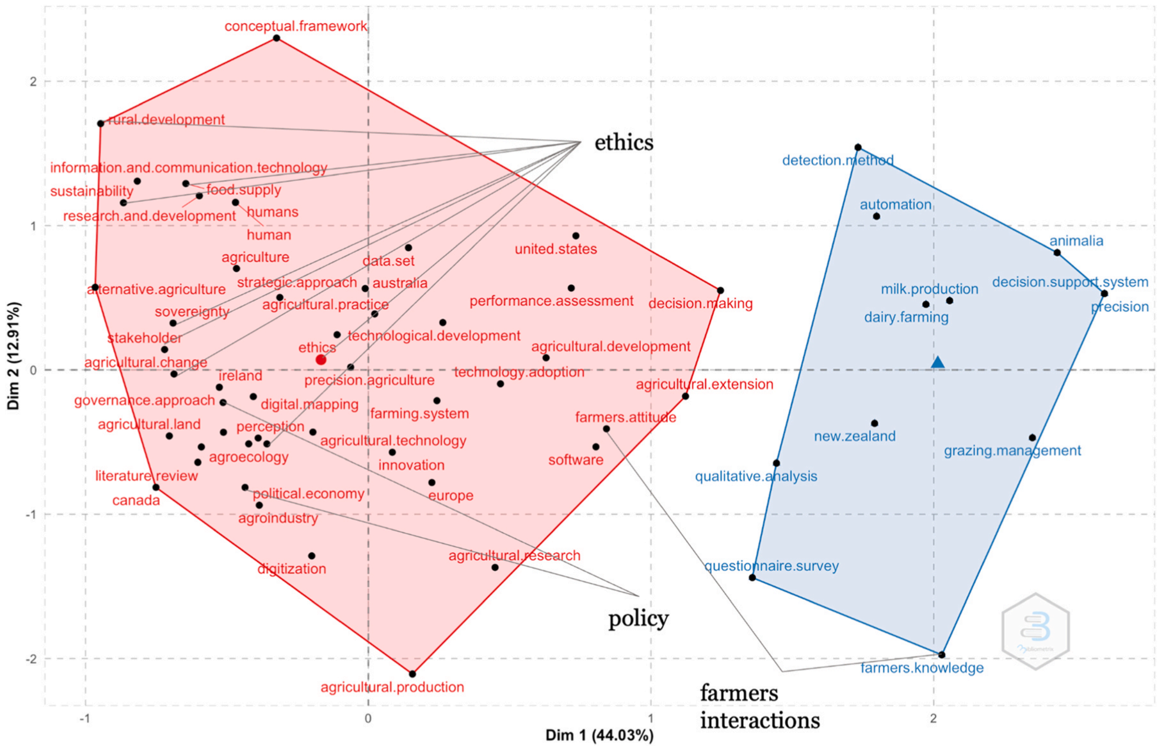

Fig. 10. Factorial map of cluster 12. Source: Created by authors using Biblioshiny.

adoption affordable.

The articles within this research theme include several groups of actors who have been overlooked in our former research themes, but are, from a **SCOT** stance, involved in the negotiation of technological artifacts. These are policy makers and public-private partnerships, start-ups and research communities. Understanding these different stakeholders as actors who all influence the interpretation of new technologies can help us gain a more nuanced understanding of the drivers and barriers of technological change. Furthermore, from an **ANT** perspective we derive that broadening the relationship between human and non-human actors and better integrating new technologies will create a nuanced understanding of how SFTs interact with different social groups and which role these stakeholders play in the process of technological change.

Thus, several questions remain for future research. The social, economic, and environmental implications of SFTs, particularly their impact on rural development, employment, and equity, require deeper exploration. Additionally, understanding how different stakeholders - farmers, policymakers, technology developers, and consumers - shape technological adoption and governance is crucial. Further research is needed to examine how SFTs disrupt and transform traditional agricultural systems. To address these gaps, Table 6 outlines theory-driven questions for future inquiry.

5. Conclusion

Agricultural systems face challenges in resource management, production efficiency, and sustainability (Dayıoğlu and Turker, 2021), and SFTs are often seen as key to addressing these challenges (Carducci et al., 2021; Moysiadis et al., 2021). Despite extensive research on SFT adoption and diffusion, a critical gap in the current literature is the lack of understanding of why exactly the adoption of SFTs happens, or rather, fails to happen (Osinga et al., 2022; Coccia and Watts, 2020; Solis-Sánchez et al., 2009). To address this lack of understanding, we unpack the current academic discourse on SFTs from a TIM perspective by a rigorous systematic literature review, encompassing 973 studies.

Thus, through this comprehensive SLR, we map the state of the art of smart farming innovation research to identify the key research themes. The identified key research themes cover a technocentric perspective, a users' perspective and a socio-technical perspective, with the technocentric perspective strongly prevailing.

We then critically analyze these themes and challenge their main research narratives, aiming to uncover substantive questions for future research (see Fig. 11). Thus, in our analysis, we reveal two important ontological premises that need problematization within the research community: (1) Researchers investigating the development of SFT technologies assume that improved functionality will lead to higher diffusion. (2) Researchers interested in the drivers and barriers of adoption assume that an adoption decision results from farmers' psychological and socio-economic characteristics. By drawing on three established theories to explain technological change, we highlight how the prevailing assumptions within the literature oversimplify the processes of technological change.

We have identified several questions for future research (see Tables 4, 5, and 6) that address a socio-technical and systemic level: What is a meaningful typology of users, and within which technological frames do these types interpret SFTs? Who else influences SFT interpretation apart from users? How do new relationships between human and non-human actors impact on-farm routines and decision-making? These questions can serve as a starting point to better understand how smart farming technologies will unfold within the agricultural socio-technical system.

The findings of this systematic literature review (SLR) carry several important implications for both academic researchers and agricultural practitioners:

First, we have outlined that improved functionality will not automatically lead to higher diffusion rates. For researchers, this implies the need to expand their analysis beyond technical performance and adoption metrics. For practitioners, especially technology providers and developers, our findings underscore the importance of user-centered innovation processes. Engaging farmers and agricultural workers early in development cycles is essential to ensure technologies are both functional and contextually relevant and address real-world farming challenges.

Second, we argue that the decision to adopt is more complex than current research suggests. For the academic community this highlights the need for more interdisciplinary studies that foster a better understanding of how social, organizational, and ethical dimensions influence the uptake and use of SFTs. Also, policymakers and agricultural support institutions must recognize that adoption is not merely a rational economic decision but is embedded in farmers' experiences, trust, and long-term strategies. Agricultural enterprises have a history of digitalization that has been linked to many challenges. Thus, initiatives promoting the adoption of SFTs, policy-makers, agricultural businesses (e.g., machine and input suppliers, AgTech Startups), cooperatives and farmer unions should focus on understanding how farmers and stakeholders perceive these technologies. This ensures they are presented in a way that aligns with farmers' values, addresses their concerns, and highlights clear, practical benefits for their specific operations.

Third, we have highlighted that the application of SFTs impacts on-farm routines, workflows and processes more significantly than it may initially appear. Therefore, we recommend scholars and farmers alike to continuously reflect on the changes these technologies bring to their operations, e.g., to the health and well-being of employees, how SFTs influence their decision-making and their fallback strategies to mitigate the risk of dependency on technology providers. As SFTs increasingly shape labor structures and decision-making routines, proactive reflection and adaptive management are critical to ensure that these tools support—not undermine—resilient and sustainable agricultural systems.

Our bibliometric analysis and interpretation of the findings have some limitations. First, we only used the SCOPUS database. Adding additional literature manually from other databases could have enhanced our analysis. Second, this literature review was conducted without the use of generative AI, due to concerns about reproducibility, trustworthiness and the potential for hallucination (Fijačko et al., 2024; Gwon et al., 2024; Farhat et al., 2023). However, the inclusion of generative AI could have offered benefits, such

Table 6
Suggested research questions for future research in research theme C.

Evolutionary Economics (EE)	*Social Construction of Technology (SCOT)*	*Actor-Network-Theory (ANT)*
Research theme C: Broaden the view – a socio-technical systems perspective		
– What are the implications of smart farming technologies for rural development and employment, and how can policymakers ensure that the benefits of technological change are distributed fairly and equitably? – How does the emergence of smart farming technologies impact the distribution of benefits and costs across different actors in the agricultural value chain, including farmers, input suppliers, and buyers? – How do science communities function as stakeholder groups and play a role in the selection mechanisms of technological change in the agricultural industry?	– How do different stakeholders, such as farmers, technology developers, policymakers, and consumers, shape the development and adoption of smart farming technologies through their values, norms and beliefs? – Which technological frames evolve around those different stakeholder groups and by whom are they established? – How do smart farming technologies influence social and cultural changes within the agricultural sector, and what are the implications of these changes for social equity, environmental sustainability, and economic development?	– What are the challenges and opportunities associated with managing the complex networks of actors involved in the development, implementation, and use of smart farming technologies, and how can these challenges be addressed through effective governance mechanisms? – How do smart farming technologies change the agency and roles of different actors of the agricultural system when compared to traditional agriculture ? – How do smart farming technologies transform the boundaries between humans and non-humans, and what are the implications of these boundary transformations for the social and environmental sustainability of agriculture?

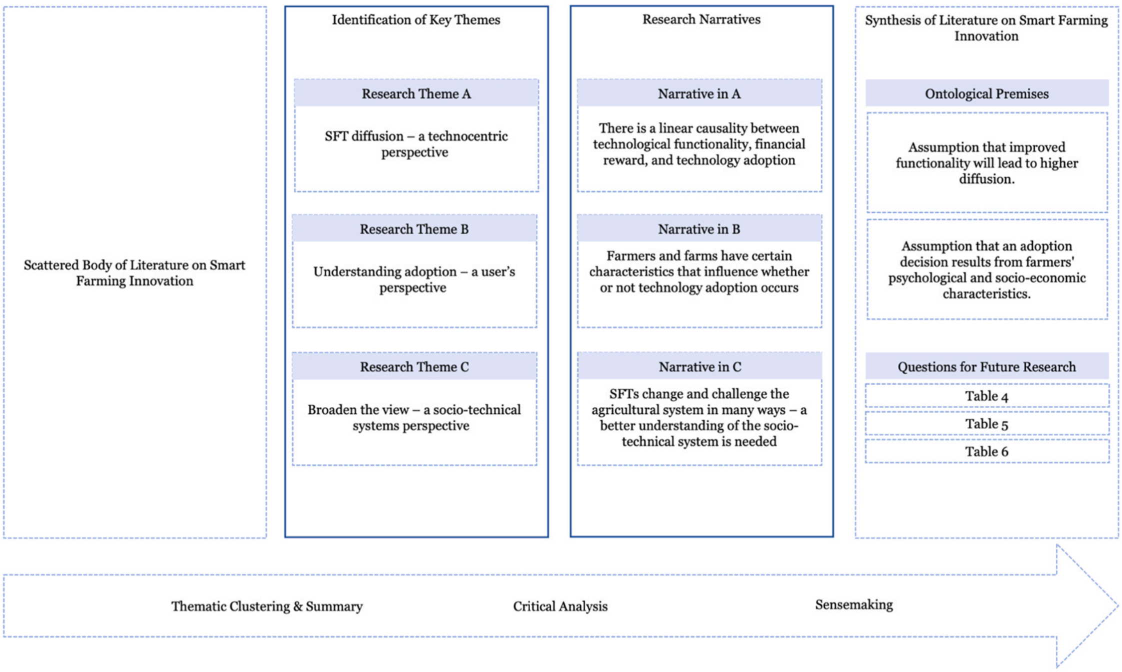

Fig. 11. Summary of Results.

as identifying novel connections across the themes, and potentially uncovering emerging topics that may not have been immediately apparent through a traditional human-centric approach. Third, we used Bruun & Hukkinen's "Integrative Framework for Studying Technological Change" (2003). We believe that this framework comes with some limitations. To our knowledge, the framework has not been updated yet to capture the integration of cyber-physical technologies in social contexts. Moreover, contrary to its name, the framework lacks an actual integration of the three different theories. Rather, the theories stand side by side and were also discussed separately by us. In addition, an institutional perspective is merely touched upon.

Still, we understand our work as an impulse for TIM scholars to start new conversations about how technological change unfolds and what its implications are for a sustainable transformation. Our research findings encourage TIM scholars to think theoretically differently (Post et al., 2020) about technological change – In order to address the grand challenges of the era of digitalization, we must build a bridge between empirical results from different domains and solid theoretical concepts. Discussing the case of smart farming, we hope this article inspires other scholars to make use of diverse theories for critical reading of existing literature and opens up new avenues for TIM research to better understand technological change.

CRediT authorship contribution statement

Lea Daniel: Writing – original draft, Formal analysis, Conceptualization, Writing – review & editing, Visualization, Data curation. **Lars Groeger:** Writing – review & editing, Conceptualization, Supervision. **Katharina Hölzle:** Supervision, Writing – review & editing, Conceptualization.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jengtecman.2025.101898.

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