

REVIEW

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A systematic literature review on socio-ecological value scorecards for advancing sustainable smart agriculture

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Abstract

Agriculture, vital for sustenance and economic stability, faces growing pressures from resource scarcity, urbanization, and a surging global population. Achieving sustainable food production necessitates integrating state-of-the-art technologies within a complex, diverse ecosystem encompassing farmers, businesses, and policymakers. A socio-ecological value scorecard is essential for informing decision-making and enhancing farming systems; yet, there is a significant gap in thoroughly examining its role in addressing agricultural challenges. This paper addresses this by presenting a systematic literature review (SLR) of 26 relevant studies, rigorously selected from an initial 1010 papers published between 2014 and 2024. Articles underwent a two-phase screening process based on specific inclusion and exclusion criteria, followed by a quality assessment criteria to ensure reliability and relevance. The review highlights the critical role of a socio-ecological value scorecard to evaluate the broader implications of agricultural activities, guiding stakeholders toward more sustainable and responsible practices. This review also explores opportunities and challenges in leveraging data-driven agricultural innovations, precision agricultural techniques, the Internet of Things (IoT), cloud computing, and artificial intelligence (AI) to enhance control, productivity, and sustainability. It emphasizes the importance of data governance and sharing to unlock the full potential of these technologies, moving beyond traditional, experience-based methods. Moreover, the review provides a comprehensive analysis and taxonomy, illustrating the current research landscape and offering insights for future studies in developing and implementing a socio-ecological value scorecard for sustainable smart agriculture. Ultimately, the study contributes to understanding how a holistic, data-driven approach can pave the way for responsible and environmentally conscious farming practices.

Keywords Socio-ecological value scorecard, Systematic literature review, Sustainable agriculture, Data governance, Digital transformation, Systems thinking



1 Introduction

Farming is imperative for people to survive and plays a crucial role in the economy [1]. In recent years, it has evolved significantly through employing state-of-the-art technologies to handle resources efficiently, produce increased yields, and make more profits [2]. Beyond food production, agriculture also has profound implications for environmental sustainability and community welfare [3]. Despite these advancements, agriculture faces major challenges. The unequal distribution of global natural resources and significant regional disparities are exacerbated by urban expansion, which leads to severe shortages of arable land in critical areas. As the global population is expected to reach 9 billion by 2050, achieving sustainable food production poses a significant challenge. Tackling this issue necessitates approaches customized to the unique socio-economic and environmental circumstances of every region or nation [4].

One promising approach to overcoming these challenges is smart agriculture, which involves utilizing Information and Communication Technology (ICT) in agriculture [5]. Smart agriculture refers to the use of AI, the IoT, big data analytics, and other advanced digital technologies to manage farming activities [6]. These technologies have a profound impact on the entire food supply chain, offering predictive analytics in farming operations, enabling real-time operational decisions, and transforming business processes to adopt innovative business models [7]. For instance, smart agriculture facilitates the resolution of challenges in crop cultivation by enabling farmers to monitor various factors such as weather conditions, soil conditions, and moisture levels. Through the internet, IoT connects diverse tools and sensors, including robots, ground sensors, and drones, enabling seamless collaboration and automatic operation [8]. In addition, smart agriculture uses artificial intelligence to make agriculture more sustainable and efficient. It relies on approaches like machine learning, deep learning, and time series analysis [9]. These technologies help with many tasks, such as choosing the right crops, predicting how much will they grow, checking if the soil is suitable, and managing water use. Moreover, machine learning aids in crop selection and management, while deep learning is used to predict harvests. Time series analysis contributes to predictions of crop demand, prices, and yields trends. Furthermore, AI systems can analyze factors like soil quality to determine optimal crop types. As a result, this shift towards smart agriculture improves productivity, efficiency, sustainability, inclusiveness, transparency, and resilience in agriculture [7].

However, the full potential of smart agriculture is hindered by various security and implementation challenges. These include compatibility problems, device constraints, and concerns about data governance [10]. These challenges in smart agriculture highlight its nature as a complex, diverse, and heterogeneous system comprising various stakeholders, advanced technologies, and intricate interactions [11]. This ecosystem includes farmers, agribusinesses, technology providers, researchers, and policymakers, each with varying degrees of influence and expertise. Given this complexity, systemic approach becomes crucial, which allows practitioners, farmers, agronomists, and other stakeholders to collaborate to understand how the entire agricultural system performs holistically, rather than focusing on individual components in isolation [12].

Building on this systemic perspective, achieving sustainability is more achievable when leveraging a comprehensive set of knowledge, technologies, and resources, including data-driven agricultural innovations and precision farming techniques, rather than

relying solely on human observation, analysis, and experiential memory, which can be inaccurate and time-consuming [13]. Yet, the escalating complexity of agricultural systems, influenced by climate fluctuations, socio-economic disparities, and heightened transparency requirements, necessitates a multifaceted approach beyond technological interventions. A compelling need arises for evaluation frameworks that comprehensively capture the interconnected environmental, social, and economic consequences of agricultural practices [14]. There is a pressing need for evaluation frameworks that capture the interconnected environmental, social, and economic impacts of agricultural practices. As argued by [15], Sustainability assessment tools must evolve technical metrics by incorporating values, objectives, and participatory methodologies that align with the lived experiences and priorities of diverse stakeholders. Similarly, [16] emphasizes the crucial role of integrated sustainability assessment frameworks in aligning farming innovations with broader societal, ecological, and economic objectives. But, current tools remain fragmented. Generic indicators may be inadequate in capturing adaptive processes within heterogeneous systems, such as smallholder agroecosystems, due to their limited capacity to account for context-specificity, multifunctionality, and diversity [17].

The primary objective of this review is to analyze existing literature and identify gaps in the understanding of how digital technologies and innovations can support sustainable agricultural practices through socio-ecological value scorecards. Furthermore, the article aims to conduct a comprehensive analysis of how data analysis, governance practices, and systems thinking can be integrated to increase agricultural sustainability. These scorecards are intended to evaluate the broader environmental and social implications of agricultural practices, serving as a practical tool to help farmers, policymakers, and stakeholders toward more sustainable and responsible practices. Additionally, a socio-ecological scorecard seeks to standardize and strengthen the role of social indicators to ensure their consistent relevance and granularity, particularly in contexts such as family farming and rural welfare. Moreover, the use of a socio-ecological scorecard promotes a systems-wide perspective and allows stakeholders to assess agricultural performance holistically rather than in isolated components. Therefore, designing a robust socio-ecological value scorecard is not just a technical task, but a strategic imperative for facilitating responsible innovation, ensuring data equity, and supporting sustainable transitions in agriculture across scales and geographies.

The review addresses research questions by using a systematic literature review (SLR) approach, which refers to a structured and step-by-step approach for gathering, critically assessing, synthesizing, and showing insights from various research studies to address specific research questions [18]. In total, 26 relevant articles were investigated in accordance with the standards of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, which provides detailed guidance on conducting systematic reviews and ensures a transparent and comprehensive analysis of these articles [19].

The scope of the article is to find answers to the research questions presented in Table 1. These research questions provide a comprehensive framework for evaluating the implications of socio-ecological value scorecards in a farming setting. Each question targets the critical aspects of this review.

The main contribution of this study is to address the development and implementation of a socio-ecological value scorecard for sustainable agriculture, focusing on:

Table 1 Research questions

RQ #	Research question
RQ1	What role does the socio-ecological value scorecard play in sustainable agricultural practices through data analysis?
RQ2	What challenges arise when applying the socio-ecological value scorecard to complex agricultural ecosystems, and how can they be addressed?
RQ3	What are the key obstacles and enablers in implementing robust data governance practices that enhance the value of socio-ecological data within farming systems?
RQ4	What technological innovations are needed to improve the accessibility and usability of the scorecard for small farmers?
RQ5	How can systems thinking create a more holistic understanding of socio-ecological systems in agriculture?

- Analyzing the role of data analysis in enhancing agricultural sustainability
- Identifying challenges and solutions in applying the scorecard to complex farming ecosystems
- Exploring the data governance practices that maximize the value of socio-ecological information in farming
- Reviewing cutting-edge technological innovations to make the scorecard accessible and usable for small farmers
- Highlighting the application of systems thinking to create a more comprehensive understanding of socio-ecological systems in agriculture
- A summary of the opportunities, challenges, and recommendations for further study in this field

This approach is grounded in a thorough literature review that identifies recurring themes essential for assessing value in socio-ecological contexts. This background will help to understand why such a tool is necessary and what gaps it seeks to address.

This study also emphasizes the obstacles and potential future research domains in the area. As far as we are aware, this study is the first research to include an SLR on a socio-ecological value scorecard covering all these areas.

The rest of the article is organized as follows: The next section explores the recent adoption of advanced technologies in agriculture and focuses on the integration of IoT, cloud computing, AI, and Big Data to develop smart agriculture. It describes how these technologies enable innovative applications, enhance productivity and profitability, and address challenges associated with sustainable agriculture. Section 3 explains our research methodology and how we conducted our review. Section 4 presents results, and six key themes identified in our review. Section 5 focuses on addressing the research questions, while Sect. 6 discusses and highlights the challenges and gaps in the research and offers recommendations and ideas for future studies. Finally, Sect. 7 provides the conclusion of this SLR.

2 Background and related works

Recently, farming and the food industry have faced major challenges caused by pandemics, global conflicts, and climate change, which disrupt food production and supply chains. These challenges underline the importance of implementing sustainable farming practices to guarantee food security and environmental stability [20]. In this context, digitalization is considered a key driver in addressing these challenges. As a result,

innovative solutions are being sought by all actors in the food supply chain to make the food system more sustainable and resilient.

2.1 Existing work on smart agriculture and digital technologies

Digitalization has the potential to amend energy efficiency and offer sustainable solutions [21]. Digital technologies such as big data, artificial intelligence, and the IoT, help reduce climate change effects by using resources like water and fertilizer more efficiently. Smart Connected Farms (SCF) networks indicate significant potential in terms of transferability and scalability in regions where farmers have access to basic requirements like sensors, data platforms, and internet connectivity [22]. These networks can be formed among local farmers while remaining flexible to incorporate different cropping systems, management practices, and environmental conditions. SCF networks provide a variety of advantages, such as timely pest control and disaster prevention, particularly helping farmers who have few resources or knowledge.

Recent technological advancements are reshaping the agricultural landscape by enabling smarter and more sustainable practices. AI-powered data collection and analysis can reveal complex interactions within natural systems, offering insights critical for sustainable agriculture and food security [13]. At the same time, the new possibilities of the IoT are also paving the way for new business models, offering unprecedented control over agricultural processes [23]. The Data-intensive management practices that utilize IoT technology are crucial for boosting productivity and sustainability [24]. In conjunction with the advancements in cloud computing, IoT technologies are accelerating the transformation towards smart agricultural practices [24, 25].

2.2 Limitations in current approaches

As global ecological and social challenges intensify, there is an urgent demand for sustainability assessment frameworks that equally address environmental, economic, and social dimensions. Current Sustainability Assessment Tools (SATs) are predominantly focused on environmental and economic factors, while social metrics are frequently neglected or inadequately tailored to the actual experiences of farmers [26]. For instance, only 25% of SAT studies include social indicators compared to 93% including environmental ones [27].

In agriculture, models such as the Common Good Balance Sheet effectively measure social and environmental aspects among stakeholder groups but have not been widely implemented [28]. Also, Integrated approaches such as crop-livestock and agroforestry systems underscore the imperative for frameworks that evaluate both social dynamics and ecological factors simultaneously [29]. Moreover, consumers are willing to pay more for food that is produced in environmentally friendly and socially responsible ways [30]. Therefore, quantifying social impacts alongside ecological ones bolsters the case for supporting diversified, equitable, and sustainable systems for both policymakers and businesses.

As agricultural systems increasingly embrace digitalization, there is a growing need to assess their sustainability. Socio-ecological value scorecards have been explored as key tools for this purpose and serve as essential tools in measuring and improving farm performance [31]. They assess activities that affect both stakeholders and the environment, considering factors like profitability, productivity, and sustainability. They look

at the operations of farming, considering its impact on the environment, society, and the economy. Socio-ecological value scorecards contribute to sustainable agriculture by enhancing food quality, reducing business costs, minimizing waste, and decreasing CO₂ emissions. These scorecards support data-driven decision-making, enabling farmers to optimize resource use and improve the overall sustainability of farming operations [32]. Despite their potential, barriers such as unequal access to data, which could lead to digital poverty and deteriorate inequalities, must be addressed. These scorecards encounter implementation challenges, particularly on diversified farms that struggle to compete with a highly specialized agri-food system when adopting and maintaining new technologies [33].

Successful data governance is essential for improving the usability and reliability of socio-ecological value scorecards. Data sharing can be adopted to obtain benefits such as facilitating precision landscape management, providing activity confirmation, enabling access to new landscapes for livestock, and integrating other enterprises into livestock operations in virtual herding [34]. However, new opportunities will require effective data management and sharing, with an emphasis on the creation of trusted models. Metrics play a pivotal role in the data revolution in agriculture and act as frameworks for creating, analyzing, and utilizing data [35]. There is a need for metrics and data strategies to be more closely aligned with the structural, practical, and cultural aspects of farming. In addition, enhancing cybersecurity for interconnected cloud-based systems is imperative [21].

Blockchain technology has been explored as a solution for enhancing transparency, traceability, and data security in agriculture. Reference [36] provides a holistic review of applications of blockchain technology in smart agriculture focusing on achieving security objectives. It proposes a thorough evaluation of security features, application domains, benefits, limitations, and the computational and communication costs linked to the analyzed rival approaches. The growing emphasis on green production principles, particularly in agriculture, reflects a broader commitment to societal progress [37]. This study illuminates the complex interplay between digital technology, fuzzy systems, and the transformation of Chinese agriculture. It also introduces a study model of Chinese green agricultural total factor productivity (ATFP) and offers a precise spatiotemporal analysis through empirical research. The findings highlight significant trends that show a disconnect between the current agricultural development path and the goals of green ATFP and underscore the need for improved sustainability in agriculture.

Innovations in digital agriculture play a pivotal role in improving the effectiveness of value scorecards. The open-source weather station (OSWS) introduces an innovative solution for weather monitoring by utilizing affordable sensors, addressing the limitations of high costs and the need for master personnel found in common technologies [38]. With its ability to provide real-time monitoring and forecasting of key environmental factors through the ARIMA model, the OSWS is invaluable for sectors like agriculture, transportation, and air quality monitoring.

A systems thinking approach is also essential for reaching a rich picture and understanding the holistic interactions in agricultural ecosystems. Authors in [39] design a conceptual framework that bridges the gaps between farm-level data and system interactions to model the adoption and diffusion of digital farming technologies in crop production. The framework is grounded in the diffusion of innovation theory and the theory

of planned behavior. It incorporates established determinants of farm-level adoption from a systems perspective and links essential factors supported by empirical evidence. Moreover, incorporating various stakeholder perspectives into the technology assessment process and considering insights that align with stakeholder interests enhance the sustainability of digital agriculture [40].

Finally, several studies have investigated the role of socio-ecological value scorecards and digitalization in agriculture. Efforts to achieve well-organized food production globally have largely relied on farm intensification and consolidation [41]. Although these attempts have promoted productivity, they have resulted in environmental harm and reduced public acceptance. Thus, digital agriculture has been suggested to harmonize environmental sustainability with enhancements in crop yield. While digital agriculture holds promise for advancing sustainable farming, the public does not currently realize its advantages [42]. Social acceptance is a crucial element in the effective advancement of novel agricultural systems. Recent studies have highlighted the significance of integrating diverse disciplines and technology readiness levels (TRLs) as assessing sustainability effects [43, 44].

2.3 Critical gaps in developing socio-ecological value scorecards

Despite significant advancements in digital agriculture, our review of existing literature reveals a fragmentation across disciplines. Prior studies have typically focused on isolated technologies, environmental indicators, or productivity gains without integrating these elements into a unified, socio-ecological value scorecard. Although research is ongoing, several gaps persist in understanding and utilizing these scorecards. While the platform founders aimed to achieve both economic and societal benefits at first, the increasing commercialization and market pressures led to the emphasizing of economic and measurable values, while less tangible, non-measurable values were deprioritized [45]. Furthermore, achieving balance between stakeholder interests and leveraging innovation is challenging due to the uncertainties and complex issues in this domain, which require in-depth analysis [46]. Existing legal frameworks need to be adapted to integrate digital transformation in agriculture, ensuring that innovations align with socio-economic goals. The literature lacks practical guidance on how to design and implement scorecard systems that are inclusive, scalable, and responsive to the complex realities of agricultural ecosystems. This review aims to address these gaps by exploring how digital innovations can be better aligned with socio-ecological sustainability goals through a socio-ecological value scorecard in agriculture.

In addition, to understand the intricate nature of modern agriculture and the role of socio-ecological value scorecard, this study considered systems thinking from a theoretical perspective. Agriculture is not merely a collection of isolated components but rather a complex, diverse and heterogeneous system. The systems thinking approach allows for a holistic understanding of how the entire agricultural system performs. Rather than focusing on individual elements in isolation, it emphasizes the interconnectedness of components such as precision farming technologies, IoT sensors, data analytics, and sustainable farming practices.

A comprehensive taxonomy of Agriculture 4.0 has been proposed, which systematizes the scholarly treatment of digitalization in agriculture and analyzes its role as an enabler of sustainability-oriented innovations and addressing existing research gaps [47].

Table 2 Comparison of the proposed SLR with existing reviews

Surveys	Sustain-ability and innovation	Data gover-nance and sharing	Enabling technologies	Digital transformation	New business models	Respon-sible digi-talization
[48]	✓		✓	✓		
[32]	✓	✓	✓	✓		✓
[39]	✓			✓	✓	✓
[21]	✓		✓	✓		
[22]		✓	✓	✓	✓	
[49]			✓	✓		✓
Our SLR	✓	✓	✓	✓	✓	✓

Table 3 Mapping of research questions to PRISMA review components

RQ #	Research question	Data items to extract	Synthesis method	Expected themes/ outcomes
RQ1	What role does the socio-ecological value scorecard play in sustainable agricultural practices through data analysis?	Descriptions of scorecard use Outcomes reported Type of data analyzed	Thematic synthesis	Benefits of scorecard in improving sustainability Operational improvements Performance metrics
RQ2	What challenges arise when applying the socio-ecological value scorecard to complex agricultural ecosystems, and how can they be addressed?	Reported barriers and challenges Factors affecting implementation Proposed solutions	Thematic synthesis	Implementation challenges Practical recommendations for application
RQ3	What are the key obstacles and enablers in implementing robust data governance practices?	Data governance frameworks Enablers and constraints Outcomes and lessons learned	Thematic synthesis	Governance challenges Enabling factors Barriers factors Policy considerations
RQ4	What technological innovations are needed to improve accessibility and usability of the scorecard for small farmers?	Technologies described Adoption challenges User feedback	Thematic synthesis	Enabling technologies Usability improvements Accessibility considerations
RQ5	How can systems thinking create a more holistic understanding of socio-ecological systems in agriculture?	Applications of systems thinking Conceptual frameworks	Thematic synthesis	Holistic frameworks System-level insights Interdisciplinary approaches Systemic barriers

Table 2 presents a comparison between this SLR with the state-of-the-art literature reviews. Notably, the existing reviews exhibit a deficiency in addressing at least one theme, whereas the current SLR comprehensively covers all themes and codes pertinent to designing a socio-ecological value scorecard.

3 Methodology

We have methodically identified relevant papers from designated research repositories to fulfill the study objectives and guarantee high review quality. Moreover, the research adheres to the recommended guidelines outlined by [19], including the following steps:

1. Search strategy
2. Identification of primary studies
3. Limitations and threats to validity

To demonstrate transparency and alignment with PRISMA guidelines, Table 3 presents the mapping of each research question to the corresponding extracted data items, applied synthesis methods, and expected outcomes.

3.1 Search strategy

In order to find the relevant literature on socio-ecological scorecards and their implications for smart agricultural practices, we explored four well-known research repositories (databases): “Web of Science”, “Scopus”, “Springer Link”, and the “IEEE Xplore”. Most research papers relevant to the given research topics are found in these repositories. Taking into account the extent of the review, we create the search query in four sets of terms shown in Table 4. Besides, every group was coupled using the “AND” operator. The “OR” operator merged search terms within the three groupings. While Group B emphasizes production, cost, sustainability, and profitability, Group A concentrates mostly on farming. Group C addresses terminology connected to systems thinking approaches; this directly supports Research Question 5 on how “systems thinking can create a more holistic understanding of socio-ecological systems in agriculture”. group D relates to terms on data and digital technologies and dashboards at last. Across all four databases, we searched using the same terms. “Data governance” and “data sharing” are central to unlocking technology's potential and are addressed by Research Question 3. “Digital technology” reflects the innovative tools used in smart farming, linked to Research Question 4's focus on accessibility for small farmers. The term “digital dashboard” was included as the socio-ecological value scorecard is conceptualized as a “central dashboard-based tool” for data integration and decision-making.

We conducted literature searches using the title, abstract, and author keywords to find the relevant literature. By executing the query, we obtained 1010 total results across all databases, as depicted in Fig. 1.

3.2 Identification and inclusion of relevant studies

We separately applied the search criteria to the repositories and retrieved the data using the search phrase in order to conduct a thorough literature study. It is worth mentioning that our initial pilot searches utilized wildcards; however, subsequent comparative analysis indicated no additional relevant variations were captured through their use. We also used language filters restricted to English, article type (limited to conference and journal articles), and publication year filters. This comprehensive search and careful filtration method helped us to effectively find relevant materials. Following that, a single article—many times—could be viewed concurrently across many databases. We

Table 4 Search query formulation

Search group	Search criterion	Rationale
Group A: Agriculture domain	“farming” OR “Agriculture” OR “Agronomy”	To ensure the literature search remained centered on the agricultural sector, which is the fundamental domain of this study
Group B: Sustainability-related	“productivity” OR “cost” OR “sustainability” OR “profitability”	To capture studies directly addressing the key metrics and objectives of a socio-ecological value scorecard, which aims to evaluate and improve these aspects in agricultural practices
Group C: Systems thinking	“system thinking” OR “holistic” OR “complexity”	To identify research employing a holistic perspective, crucial for understanding agriculture as a complex, diverse, and heterogeneous system
Group D: Data related	“data governance” OR “data sharing” OR “data ownership” OR “digital technology” OR “digital dashboard”	To cover the technological and governance dimensions vital for data-driven smart agriculture
Search query	“(Group A)” AND “(Group B)” AND “(Group C)” AND “(Group D)”	

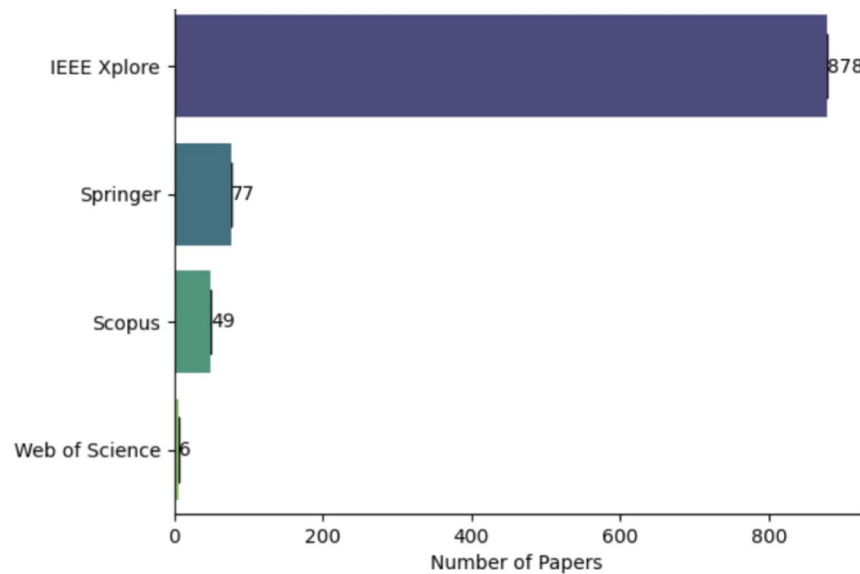


Fig. 1 Number of research papers across academic repositories

Table 5 Inclusion and exclusion criteria

Inclusion criteria	Exclusion criteria
Type of publication	Not well-defined
Timeframe (2014–2024)	Not about agricultural practices intersect with data governance practices
Journal or conference paper	Not about issues of socio-ecological data in the context of sustainable agriculture

therefore deleted the duplicate papers and utilized the remaining 1004 ones for further screening and selection criteria. Using many methods, including the “EndNote” tool for duplicate removal and discovering six duplicates, we guaranteed the right count of duplicates. Furthermore, two steps define the paper screening and selection process. In the initial step, reading the title and abstracts, guided all paper selection. A full article reading was done in the second phase.

In the first phase, the paper screening and selection criteria of the remaining 1004 articles were analyzed by the authors. The aim of this phase is to isolate studies that closely align with the specified scope of the review. Therefore, we applied the exclusion and inclusion criteria to the selected articles, as mentioned in Table 5. After applying the exclusion criteria, a total of 968 articles were excluded. Thereafter, 36 articles, including 3 journal articles, 2 conference articles, and 5 book chapters, were finalized for screening. At this stage, full-text articles were downloaded by the authors. Subsequently, 6 articles were excluded due to the unavailability of full-text articles.

Following the completion of phase 2, the 30 shortlisted articles were further scrutinized by applied quality assessment criteria (QAC) mentioned in Table 6. The quality assessment was done by thoroughly reading the full-text articles. As a result, 6 papers were removed.

These criteria were designed by the authors to evaluate the clarity of research objectives and the methodological soundness of each reviewed paper; they are tailored to the objectives and context of this SLR. For instance, QAC2 refers explicitly to the methodology used in each of the reviewed papers, not the methodology of the present systematic review. Authors independently used the specified guidelines shown in Table 6, after

Table 6 Quality assessment criteria

QAC#	Quality assessment criteria
QAC 1	Are the research objectives clearly articulated?
QAC 2	Is the research methodology well-defined?
QAC 3	Does the study explicitly address the specific domains of agricultural ecosystems in which sustainable agricultural practices intersect with data governance practices?
QAC 4	Does the study properly discuss the issues of socio-ecological data in the context of sustainable agriculture?
QAC 5	Does the conclusion reflect the research findings and future research trends?

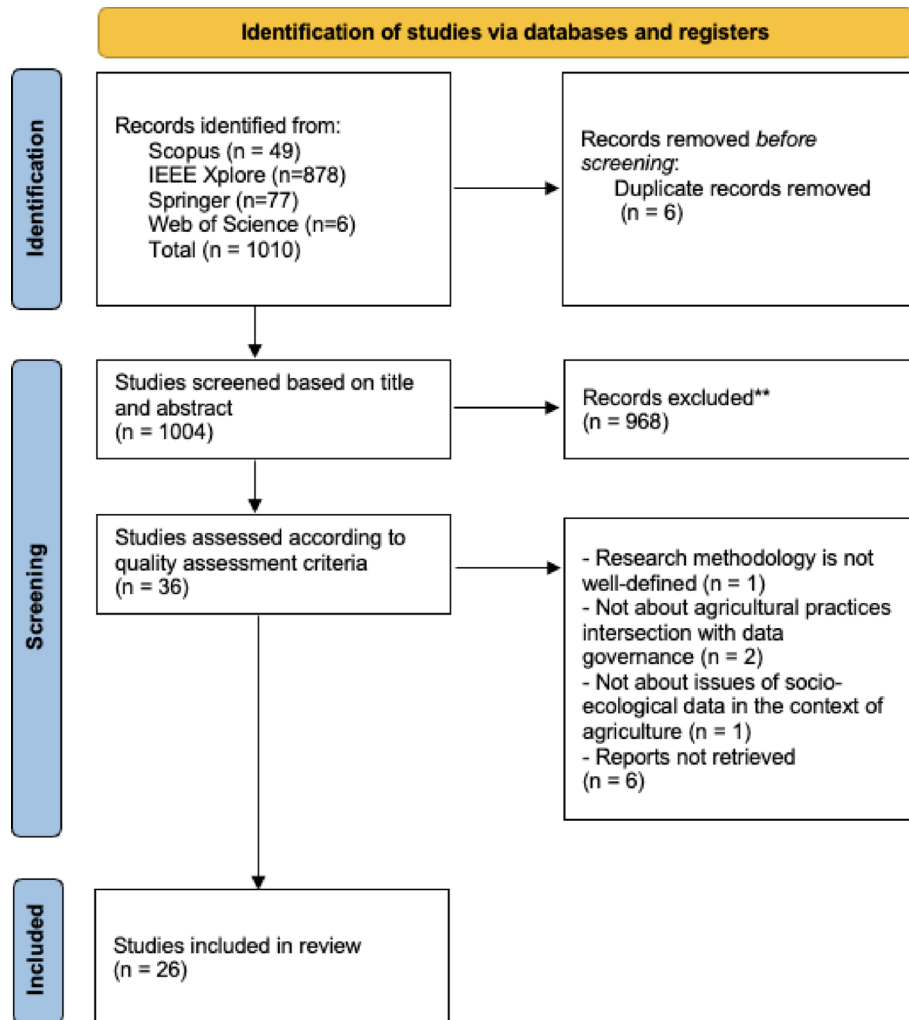


Fig. 2 PRISMA search methodology

reading the full-text papers. Giving each specified five questions of QAC scores of zero and one allowed one to evaluate the quality of the articles. A zero-score signified that the selected article did not meet the specific requirements, while we assigned one score to those that did. After assigning zero and one scores to each paper, we calculated the sum of individual articles. Those studies that scored less than 2.5 were excluded from further data extraction.

Finally, using the PRISMA framework, 26 papers satisfy the requirements for inclusion in the systematic literature review. Figure 2 illustrates the PRISMA diagram of our

research, which graphically depicts the whole process from data retrieval at first to data filtering of the useful data. It also provides a concise summary of the flow information, including identified records, screened, evaluated for eligibility, and incorporated into the final analysis.

All the 26 selected publications are journal articles. Figure 3 illustrates the visual analysis of published journal articles categorized by year.

Figure 4 illustrates the numerous publishing venues for research addressing the topic of this review. In Table 7, we present a detailed summary of the 26 included papers, categorized by year, publisher, and relation to the RQs.

3.3 Limitations and threats to validity

Database selection: The prominent research databases used for article selection in our study were Scopus, Web of Science, IEEE Xplore, and Springer. These databases emphasize reliability and relevance concerning the topic of enhancing sustainable farming through socio-ecological value scorecards, guaranteeing access to a wide array of peer-reviewed, high-quality publications from many fields. Although our emphasis was on these research databases, it is essential to acknowledge other repositories, such as Google Scholar, which is esteemed for its extensive indexation of research publications. This database was not included in the research. Moreover, for this study, only peer-reviewed journal articles, conferences, and book sections are selected. Scientific studies that are not peer-reviewed are not included.

Timeframe for the selected research: We have only investigated research over the last ten years, namely from January 1, 2014, to October 1, 2024. We excluded articles published before 2014 since our search did not return enough relevant studies in the context of our study that may have provided us with adequate information to address the research questions, critically assess the evidence, and make suitable conclusions. We also emphasize that conference papers presented prior to October 1, 2024, that may not have been published by the study's cut-off date were thus excluded from our literature review.

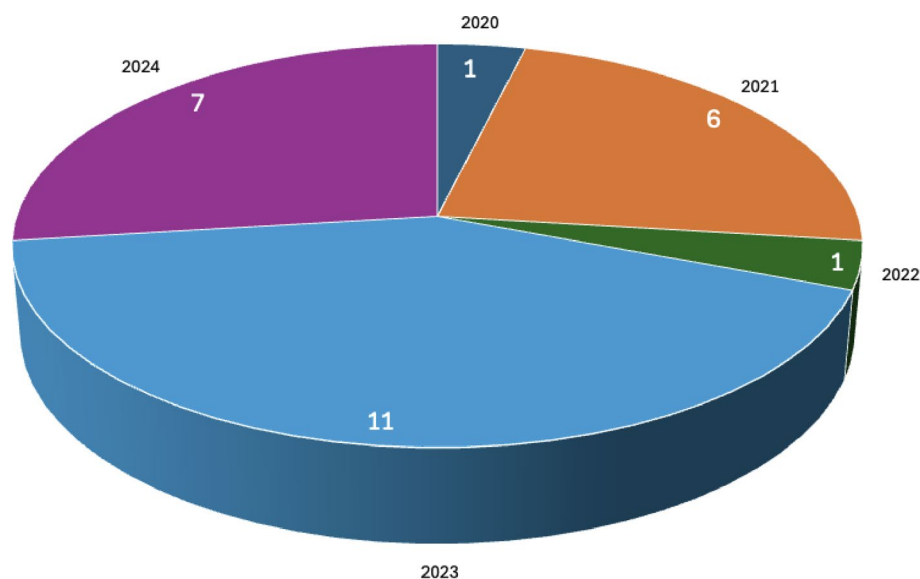


Fig. 3 Published journal articles categorized by year

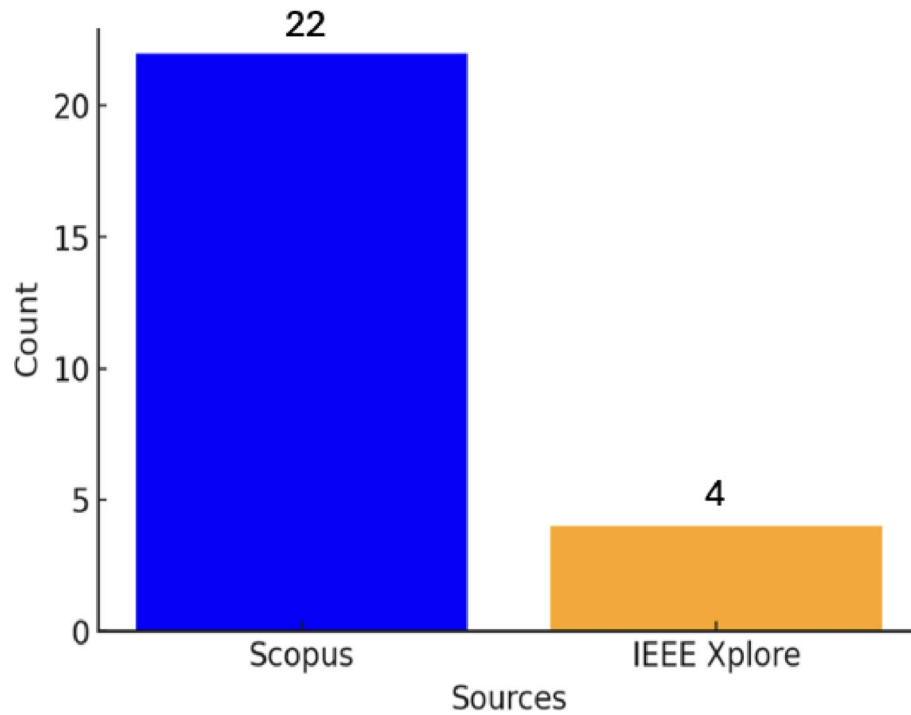


Fig. 4 Articles categorized by publishing venues

Table 7 A detailed summary of the 26 included studies

Reference	Year	Publisher	Relation to RQs
[34]	2024	Scopus	RQ1-RQ5
[33]	2024	Scopus	RQ2, RQ3, RQ5
[22]	2024	Scopus	RQ1-RQ5
[35]	2024	Scopus	RQ2, RQ3, RQ5
[50]	2024	Scopus	RQ3, RQ5
[13]	2024	Scopus	RQ1-RQ5
[37]	2024	Scopus	RQ2, RQ3, RQ5
[32]	2024	Scopus	RQ2-RQ5
[51]	2023	Scopus	RQ1, RQ3, RQ5
[49]	2023	Scopus	RQ4
[52]	2023	Scopus	RQ1, RQ3, RQ5
[53]	2023	Scopus	RQ3-RQ5
[46]	2023	Scopus	RQ3
[45]	2023	Scopus	RQ1-RQ3, RQ5
[54]	2023	Scopus	RQ5
[38]	2023	Scopus	RQ4
[41]	2022	Scopus	RQ2, RQ3, RQ5
[55]	2021	Scopus	RQ2, RQ3, RQ5
[21]	2021	Scopus	RQ1-RQ4
[39]	2021	Scopus	RQ3, RQ5
[48]	2021	Scopus	RQ3, RQ5
[47]	2021	IEEE Xplore	RQ2, RQ3, RQ5
[40]	2021	IEEE Xplore	RQ3, RQ5
[56]	2020	Scopus	RQ3-RQ5
[57]	2020	IEEE Xplore	RQ3-RQ5
[36]	2020	IEEE Xplore	RQ3, RQ5

Language consideration: We excluded articles by focusing on those written in English. Language restrictions constrain our study, perhaps resulting in the loss of some valuable research.

By clearly defining our QAC, employing independent and structured assessment by the authors, and transparently acknowledging the limitations related to language, time-frame, and database selection, we have sought to minimize bias and enhance the validity and reliability of our review findings.

4 Thematic analysis

The credibility of SLR findings is necessary for achieving the objectives of the study, as a lack of trust among the readers can undermine their reliability [18]. To ensure credibility in this SLR, thematic analysis was employed to categorize and synthesize themes for qualitative evaluation. Thematic analysis is a qualitative research technique utilized to identify, analyze, and understand repeated patterns of meaning, often referred to as themes, or topics, and ideas across multiple studies, allowing for a more comprehensive understanding of the research landscape [58]. This process consists of 6 consecutive steps, which are: becoming familiar with the data, generating initial codes, searching for themes, reviewing themes, defining themes, and assigning names to the themes. In this study, the process resulted in the identification of six key themes explored in detail in the further sections. To fulfill this, after we read the full content of the 26 selected papers, they were grouped, and patterns were identified and categorized into themes. Since the themes and relevant studies were concluded, the next step involved a comprehensive explanation and analysis of the themes. Every author participated in discussions to finalize and name the themes, continuing the conversation until agreement was achieved. In Fig. 5, a taxonomy is provided to visualize the identified main themes and sub-themes to explain the current situation of current research in developing a socio-ecological value scorecard.

Sustainability and Innovation emphasizes sustainable farming practices and digital innovation, while *Data Governance and Sharing* focuses on data-driven agriculture, privacy regulations, data approaches, and secure data-sharing technologies like blockchain. The role of *Enabling Technologies* in modernizing agriculture is imperative through smart agriculture and IoT and digital tools. Smart agriculture leverages IoT and data analytics for precision agriculture, including smart irrigation and environmental monitoring. Digital tools such as fuzzy systems, climate-smart agricultural solutions,

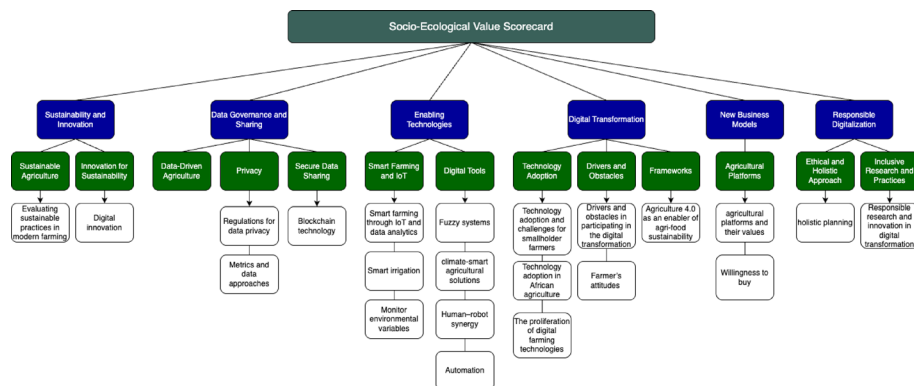


Fig. 5 Taxonomy with the main themes and sub-themes

human–robot synergy, and automation can increase productivity and sustainability in farming practices. These technologies shape the foundation for a more data-driven agricultural ecosystem. On the other hand, *Digital Transformation* centers on the adoption and challenges of implementing these technologies. Technology adoption looks at the integration of digital solutions among smallholder farmers, while drivers and obstacles state the factors affecting participation in digital farming, including attitudes of farmers and the proliferation of digital technologies. Meanwhile, *New Business Models* explore Agriculture 4.0 as a sustainability enabler and the role of agricultural platforms in consumer decision-making. Finally, *Responsible Digitalization* ensures an ethical and inclusive approach, promoting holistic planning and responsible research in digital innovation. This taxonomy provides a comprehensive lens to assess how digital advancements can drive sustainable agricultural practices while addressing governance, adoption challenges, and ethical concerns.

Table 8 summarizes the identified themes and their corresponding connection with the reviewed papers.

4.1 Theme 1: Sustainability and innovation

This theme underscores the imperative of balancing technological innovation with ecological stewardship. The literature indicates that digital innovation ecosystems are key areas of innovation that involve the integration of complex IT systems and the participation of different stakeholders in the context of the agri-food domain [52]. An empirically informed framework for analyzing and designing sustainable digital innovation ecosystems is presented through a longitudinal study of European public–private innovation projects conducted from 2011 to 2021. This framework identifies key factors that drive successful digital transformation in this domain, which consists of innovation strategy, organization, networks, and infrastructures.

The combination of digitalization through technologies presents many opportunities and challenges in promoting sustainability [21]. With the growing incorporation of digital technologies into agricultural practices, data creation, analysis, and decision-making frameworks are becoming essential to improving sustainability. A key consideration is the application of these technologies to address serious issues in the food-water-energy nexus, including sustainable food production, clean water access, and renewable energy generation. These technologies can assist in advancing sustainable practices and accessibility for poor communities. However, while these innovations offer great potential, attention must be given to the implications of digital inequality and the need for robust cybersecurity measures to protect interconnected systems. These innovations are aligned with the objectives of Agriculture 4.0, which highlights the utilization of advanced digital technologies for precision agriculture [48]. This approach supports the shift from traditional farming to more efficient, data-driven practices. Further, these

Table 8 Themes and their connection to the relevant studies

Theme	Papers
Sustainability and innovation	[21, 40, 48, 52]
Data governance and sharing	[13, 33, 35, 36, 46]
Enabling technologies	[22, 32, 37, 38, 49, 51, 57]
Digital transformation	[39, 47, 50, 53, 54, 56]
New business model	[21, 41, 45]
Responsible digitalization	[34, 55]

technologies are crucial in tackling the global issues of climate change, resource scarcity, environmental degradation, and fostering sustainable agricultural development by enhancing crop yield, improving quality, and reducing resource consumption.

As part of the broader theme, evaluating Sustainable Modern Agricultural Technologies (SMATA) is a complex task, mainly when dealing with unclear or unsure input from stakeholders during sustainability evaluation. This uncertainty needs to be considered quickly in the development of decision-making processes, while the evaluation must take into account different and sometimes opposing views from stakeholders. To ensure trustworthiness in evaluation, approaches such as q-rung orthopair fuzzy sets (q-ROFS) are employed [40].

4.2 Theme 2: Data governance and sharing

As digital technology advances, understanding how different groups, like small farmers and large agribusinesses, interact with and manage agricultural data is becoming more important [33]. Moreover, there is a need to create secure systems to ensure fair access to and responsible use of this data for everyone involved. The use of digital tools in farming, particularly in systems that have different types of farming, creates complex networks of people, technology, and physical resources. These networks affect how data is collected, shared, and governed in agriculture.

Standardizing data collection and data quality and addressing concerns surrounding ownership and privacy are foundational for building trust and enabling broader data sharing [13]. Trust-building mechanisms, such as data anonymization and the involvement of impartial organizations like universities, have been proposed to encourage farmer participation. Furthermore, developing innovative business models and regulatory frameworks that incentivize data pooling and sharing is imperative to realizing the potential of large-scale agricultural datasets.

Despite the benefits of emerging technologies in revolutionizing the agricultural sector by allowing precise data collection and processing that enhance decision-making and improved farming practices, data governance and sharing in agriculture face several critical challenges and opportunities [46]. Economic and social restrictions encompass reluctance of farmers to share data due to a lack of demonstrated value, suspicion of data aggregation organizations, and concerns about misuse, such as competitive disadvantages or increased regulatory supervision. The introduction of legal and regulatory obstacles that demand a balance between fostering innovation and protecting the diverse interests of stakeholders, including farmers, companies, governments, and consumers.

Moreover, the adoption of sustainability metrics in agriculture underscores the significant importance of data governance frameworks in the data revolution within this sector [35]. However, the implementation of these metrics encounters several challenges, especially when it comes to aligning data-driven approaches with the intricate, localized conditions of agriculture. Resistance from farmers is frequently rooted in worries regarding data ownership and the enforcement of externally created metrics that do not align with their traditional practices. Therefore, it is important for governance structures to consider these factors and ensure that farmers have greater control over how metrics are developed, implemented, and used. Neglecting these aspects can hinder the effectiveness of data-driven approaches to enhancing sustainability in agriculture.

4.3 Theme 3: Enabling technologies

This theme captures the range of technological innovations that support the operationalization of smart agriculture. Key technologies, which encompass AI, Big Data, IoT, blockchain, nanotechnology, robotics, and Remote Sensing (RS), are improving crop resilience and reducing greenhouse gas emissions [32].

Additionally, new technologies like blockchain offer promising advancements in enhancing the food supply chain. Blockchain technology has the capability to improve information security in agriculture and offers decentralization, persistence, anonymity, and auditability [36].

Also, growing industrialization and unforeseen global disruptions have accelerated the adoption of agricultural robots [51]. These automated solutions can help increase yield, they also pose societal challenges, particularly in rural areas facing unemployment and resistance to digitalization.

With the growing integration of technology in farming practices, a strong focus has been directed towards the usage of ICTs to improve agricultural output, with smallholder farmers employing different digital tools, such as mobile devices, television, and radio, along with innovative technologies like GIS, RFID, Precision Agriculture, and GPS [50]. Also, an affordable, easy-to-maintain station using inexpensive sensors to provide reliable data for agriculture, transport, and air quality through web-based interface, which increases usability [38].

Automation in agriculture has indicated significant potential to mitigate the environmental impacts of farming while increasing the ability of farmers to adapt to economic challenges. For instance, Automatic Feeding Systems (AFSs) improve both the precision of ruminant feeding and reduce the workload for workers [49], leading to increased production, improved farm profitability, and minimized feed waste. Meanwhile, advancements in information and communication technologies, precision agriculture, and data analytics have paved the way for the development of SCFs and farmer networks [22]. Main parts of SCFs contain high-speed connectivity, IoT sensors for data collection, and computational paradigms such as edge, fog, and cloud computing, which are supported by innovative wireless technologies to boost farm productivity, profitability, and resilience to detrimental climate events.

Combining digital technologies with fuzzy systems boosts agricultural productivity. An agricultural total factor productivity (ATFP) analysis illustrates reliance on labor and natural resources [37]. Moreover, IoT-driven precision agriculture improves performance, as seen in a smart irrigation system optimizing water use and crop management, confirming IoT and energy harvesting in sustainable farming [57].

4.4 Theme 4: Digital transformation

Agriculture 4.0 could be a major breakthrough for the entire agri-food industry [47]. It has the power to significantly transform how food is produced and the entire food supply process, which brings benefits to the environment, society, and economy. Moreover, digitalization has the potential to make a revolution and change farming practices and add more value to agricultural data [59]. Digital farming utilizes data-driven approaches with big data and cutting-edge technology to boost farming practices. They assist farmers in enhancing productivity, accessing markets, managing finances, optimizing supply

chains, and dealing with crops post-harvest. These instruments also utilize resources more effectively, minimize waste, aid in decision-making, and reduce expenses [54].

Nevertheless, smallholder farmers mainly utilize low-tech digital technologies, which encounter several obstacles linked to end-user restrictions, service provider issues, and technological limitations. Although digital transformation is emerging as a game-changing factor in agriculture, there are several substantial challenges that should be addressed, including high costs for both service providers and farmers, as well as risks for those who choose not to participate [50].

Furthermore, recent studies emphasize the growing incorporation of digital technologies in smallholder agriculture in South Africa, with a focus on e-readiness, digital tools, and the challenges encountered by farmers. Resource limitation, lack of experiment among farmers as forefront and unreliable digital infrastructure are other obstacles predominantly on the African continent [53].

4.5 Theme 5: New business models

Beyond digital technology adoption and data-driven advancements, innovative business models are critical to the success of digital transformation in agriculture. There is limited practical knowledge regarding how innovation ecosystems develop in agriculture. [52] seeks to assist by providing a practical structure derived from a long-term investigation of various agri-food initiatives. The aim is to present a way to understand and develop successful innovation ecosystems within the agri-food industry to promote innovation objectives.

Complementing this perspective, human–robot synergistic systems present a socially viable alternative by fostering collaboration between humans and automation [51]. Adopting systems thinking makes it possible to explore the complex interconnections and feedback that influence the spreading of automation, including both conventional automation and human–robot collaboration.

Within this theme, the widespread adoption of digital farming technologies is crucial in transforming agricultural systems to attain sustainability. Grasping these processes in a comprehensive manner necessitates combining insights from both empirical studies on farm-level adoption and agent-based modeling techniques. A conceptual framework has been created that combines empirical data on technology adoption [39]. This framework connects the gap between data-driven farm-level research and model-based studies. Aside from its theoretical contributions, this framework provides practical insights for policymakers by identifying critical intervention areas where policy actions can improve the spread of digital technologies.

Recent research on digitalization in the industry underscores multiple advantages, such as innovative methods for data-driven value creation, chances to address challenges like sustainability and traceability, increased learning among stakeholders, and increased efficiency throughout the overall value chain [45]. The expansion of digital platforms in agriculture involves complex discussions about economic and social values. These values are classified into two groups, which are society beneficiary and profit generator. This gap poses difficulties in developing business models [45]. Nevertheless, when platform creators pursue funding and partnerships, they often prioritize quantifiable elements that attract investors. These obstacles emphasize the difficulty of balancing profit and

social responsibility and indicate the necessity to reconsider how innovation is appraised in the agri-food sector.

4.6 Theme 6: Responsible digitalization

Responsible innovation frameworks emphasize the importance of social acceptance to address concerns related to animal welfare, data privacy, and regulatory compliance [34]. While digitalization has significant potential, it is not completely beneficial in all contexts. Its outcomes often include complex, unexpected consequences that require careful consideration. A responsible approach to digitalization emphasizes the need for a deeper understanding of these effects, along with proactive anticipation of unknown impacts to promote sustainable farming practices [55].

In addition, [51] indicates that engineers and manufacturers ought to work alongside legislative bodies and agricultural groups to create regulations focused on safety, especially regarding human–robot collaboration in agriculture. It also mentions the significance of financial assistance, like subsidies or tax breaks, to lessen the monetary obstacles for adopting automation in agriculture. Besides, raising technological understanding through training and educational initiatives for landowners and workers is crucial to promote the digitalization of agriculture, which helps stakeholders in adopting robots effectively in farming practices.

Finally, cybersecurity plays a pivotal role in smart agriculture, particularly when it comes to the integration of IoT and blockchain technologies. Security systems based on blockchain enhance data safety, traceability, and resource management. Consequently, a comprehensive blockchain security framework designed to address significant cybersecurity challenges in the agricultural sector [36].

5 Results

5.1 Answers to research questions

In the following sections, we expand on the results from the research questions that were critical to this systematic review. To synthesize the thematic findings of this review, Fig. 6 presents a summary of the six core themes in correlation with the research questions.

RQ1 What role does the socio-ecological value scorecard play in sustainable agricultural practices through data analysis?

The comprehensive analysis of Enabling Technologies (Theme 3), Data Governance and Sharing (Theme 2), and Digital Transformation (Theme 4), as presented in our thematic analysis, collectively illuminate the pivotal role of socio-ecological value scorecards in sustainable agriculture through data analysis.

Specifically, insights from Theme 3 (Enabling Technologies) reveal how digital technologies such as artificial intelligence, Big Data, and the Internet of Things are fundamental. The scorecard, acting as a “central dashboard-based tool,” leverages these

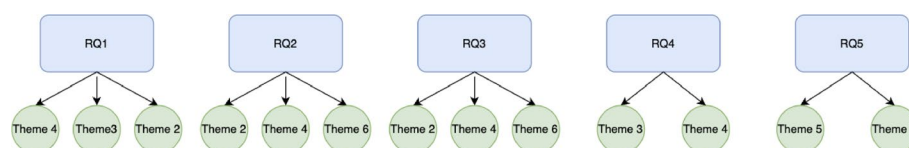


Fig. 6 Relation of identified themes and research questions

technologies for accurate assessment and monitoring of sustainability metrics in agriculture [51]. For instance, machine learning and simulations, as highlighted under this theme, enhance decision-making by identifying trends and optimizing resource utilization [22]. Furthermore, digital tools like smartphone applications, discussed in relation to enabling technologies, facilitate real-time monitoring and knowledge sharing among farmers, scientists, and technical experts, improving decision-making from production to distribution [32].

The critical role of “data analysis” in the scorecard’s function is further informed by Theme 2 (Data Governance and Sharing). This theme underscores how the scorecard facilitates data sharing and adds value to data through technology, enabling precise assessment of environmental, economic, and social effects [35]. The review emphasizes that “reliable and well-structured data empowers scientists to investigate intricate interactions, forecast trends such as climate change impacts, and establish cross-field partnerships”, directly contributing to the scorecard’s efficacy [13].

Lastly, the findings related to Theme 4 (Digital Transformation) highlight how the adoption of data-driven approaches with big data and cutting-edge technology, facilitated by the scorecard, boosts farming practices by optimizing resource use and minimizing waste, thereby enhancing productivity and sustainability [53]. The integration of diverse sensor types into automated reporting systems, for example, actively confirms enhancements in environmental and animal management practices, which are core to the scorecard’s utility.

RQ11112 What challenges arise when applying the socio-ecological value scorecard to complex agricultural ecosystems, and how can they be addressed?

Applying the socio-ecological value scorecard to complex agricultural ecosystems indicates several challenges, such as system complexity, data ownership concerns, unintended consequences of digital technologies, degradation of farmer autonomy and sense of identity, and power imbalances [55, 60, 61]. The interconnected nature of agriculture, encompassing multiple stakeholders and domains, renders it challenging to comprehensively assess its impacts. Moreover, agricultural data is gathered by various groups, each with its own needs and interests. Some may want to control the data, while others need it for different purposes [13].

The challenges inherent in applying a socio-ecological value scorecard to complex agricultural ecosystems are extensively highlighted by insights from Digital Transformation (Theme 4), Data Governance and Sharing (Theme 2), and Responsible Digitalization (Theme 6). These themes collectively reveal the multifaceted obstacles, ranging from technological integration to socio-economic impacts.

System complexity and data challenges: A primary challenge is the inherent complexity of agricultural ecosystems, encompassing diverse stakeholders and domains, which makes a comprehensive impact assessment difficult. This is further exacerbated by the inconsistency and gaps in historical farm data, which originates from heterogeneous sources such as agricultural machinery, remote sensing, traditional farm records, and even social media [13]. Integrating this diverse data into a unified, standardized system presents considerable challenges, as existing initiatives often focus more on data collection and accessibility than effective integration. Theme 2 (Data Governance and Sharing)

underscores how collecting agricultural data by various groups, each with unique needs, contributes to these integration issues, particularly concerning data ownership.

Unintended consequences and farmer autonomy: Insights from Theme 6 (Responsible Digitalization) and Theme 4 (Digital Transformation) reveal the unintended consequences of digital technologies. Farmers recognize that digital tools may not always align with their actual needs. Implementing novel standardized digital tools, such as the value scorecard, without full farmer control, can pose a potential threat to their sense of identity, independence, and creativity in managing resources and workforce [35]. Furthermore, the shift from traditional, experience-based farming to data-driven approaches can be disruptive, as farmers frequently rely on practical experience and intuition. This creates a tension that must be carefully managed to ensure the scorecard genuinely enhances knowledge rather than undermining farmer expertise.

Economic, social, and value imbalances: The complexity of digital transformation in agriculture also introduces challenges related to high costs for service providers and farmers, as well as risks for non-participants. Theme 5 (New Business Models) highlights that the increasing commercialization and market pressures often lead to the prioritization of economic and quantifiable values over less tangible social and environmental benefits [45]. This imbalance influences which values and stakeholders gain prominence, often favoring commercial interests.

RQ3 What are the key obstacles and enablers in implementing robust data governance practices that enhance the value of socio-ecological data within farming systems?

The implementation of robust data governance practices in farming systems is a core focus of Data Governance and Sharing (Theme 2), with additional insights from Digital Transformation (Theme 4) and Responsible Digitalization (Theme 6). This section details the intertwined obstacles and enablers.

Key obstacles:

- Technological complexity and economic investment: Implementing robust data governance is hampered by technological complexity, high economic investment, and the significant need for farmer adaptation and training [62].
- Access barriers and digital illiteracy: Many farmers, especially in rural areas of developing countries, struggle with access to technology, which puts them at a disadvantage. Key barriers include poor internet connectivity, lack of digital skills, difficult-to-use applications, and digital illiteracy [62]. If unaddressed, these issues can lead to digital poverty [21].
- Lack of standardization and interoperability: The absence of standardized solutions creates interoperability challenges, making it difficult to develop cohesive governance frameworks for socio-ecological data [62]. Variations in the extent of digital adoption across farms further impede a unified data ecosystem.
- Privacy, trust, and ownership concerns: Farmers' hesitancy to share data beyond their operations, due to concerns regarding privacy and trust, weakens collaborative frameworks. Issues related to data ownership, control, and trust in digital innovations are critical [34]. Legally, there remains unclarity about the difference between data creation and intellectual property rights in information systems, alongside vague distinctions between commercial farming data and private information. This means, for instance, that while combining farm data is crucial for large-scale decision-

making, farmers are often hesitant to share due to privacy and competition, and even “anonymized” farming data can still reveal farm identities [22].

- Resistance to change and financial burden: Resistance to adopting new technologies, combined with their financial burden, presents further challenges [33]. Overreliance on digital tools may also reduce interpersonal engagement in decision-making processes.

Key enablers and addressing obstacles:

- *Policy and incentive mechanisms:* Overcoming these obstacles requires transparent policies, incentive mechanisms, and farmer engagement strategies to encourage participation in data-driven agricultural practices.
- *Secure infrastructure:* The necessity of secure data protocols and reliable networks is crucial for efficient data collection, reporting, and sharing, which are key elements in fostering innovative and sustainable agricultural business models. Blockchain technology, highlighted within Theme 2 (Data Governance and Sharing), offers promising advancements for enhancing information security in agriculture, providing decentralization, persistence, anonymity, and auditability.
- *Holistic approach:* A holistic approach that integrates technological advancements with community engagement is essential to establish robust data governance practices, fostering widespread adoption and long-term success.
- *Support and integration:* Subsidies, cooperative assistance, and the integration of advanced technologies like AI are policies and strategies that can enhance the accessibility and usability of data. A robust data governance framework is vital to guarantee fair data access, safeguard privacy, and promote collaboration, thereby increasing the value of socio-ecological data.

RQ4 What technological innovations are needed to improve the accessibility and usability of the scorecard for small farmers?

The technological innovations required to improve the accessibility and usability of the socio-ecological value scorecard for small farmers are primarily addressed under Enabling Technologies (Theme 3), with crucial considerations for adoption and challenges drawing from Digital Transformation (Theme 4).

Enhancing Scorecard Functionality and Insights:

- *Advanced analytics and sensing:* Technologies such as Remote Sensing (RS), Big Data, and AI are imperative as they enhance scorecard functionalities by enabling precise crop monitoring, predictive modeling, and real-time decision-making [32]. They facilitate the detection of critical issues like water stress, pest outbreaks, and climate-related risks, providing small farmers with timely and actionable insights. Furthermore, AI-driven analytics can support genome analysis for developing climate-resilient crops, significantly boosting long-term agricultural sustainability.
- *Real-time data and operational efficiency:* IoT-based real-time data collection can make the scorecard more dynamic and responsive, allowing for continuous monitoring and adaptive management [22, 39]. Robotics contribute to operational efficiency through automated harvesting and targeted spraying.
- *Sustainability-focused innovations:* Nanotechnology can enhance soil health, precision fertilization, and carbon sequestration, optimizing nutrient efficiency

[56]. Blockchain technology improves transparency by supporting food system traceability, crucial for validating sustainable practices.

Improving accessibility and usability for small farmers:

- *Cost-effectiveness and user-friendliness*: Despite their immense advantages, it is essential that these innovations are user-friendly and cost-effective to encourage their widespread adoption among small-scale farmers. For instance, the development of affordable, easy-to-maintain solutions like open-source weather stations that utilize inexpensive sensors directly addresses the high costs of traditional monitoring systems, improving usability for small farmers.
- *Addressing adoption barriers*: To make sure small farmers can effectively adopt these tools, barriers such as high costs, digital literacy gaps, and infrastructure limitations must be addressed. This connects with the challenges highlighted in Digital Transformation (Theme 4), particularly concerning technology adoption and the obstacles farmers face.
- *Collaborative ecosystems and training*: Multi-stakeholder collaboration is crucial to create supportive environments that promote affordability, accessibility, and tailored training for farmers.
- *Environmental responsibility of digital tools*: Future research should also focus on improving energy efficiency in devices and employing renewable energy sources to decrease carbon emissions, mitigating the negative environmental effects of digital technologies themselves.

RQ5 How can systems thinking create a more holistic understanding of socio-ecological systems in agriculture?

The application of systems thinking to create a more holistic understanding of socio-ecological systems in agriculture is a core tenet of Responsible Digitalization (Theme 6), emphasizing holistic planning and the consideration of complex interactions. It also aligns with aspects of New Business Models (Theme 5) by exploring complex interconnections.

Framework for Holistic Analysis:

- *Interconnectedness and feedback loops*: Systems thinking provides a qualitative framework for analyzing complex systems, focusing on interconnected cause-effect relationships, feedback loops, and underlying mental models. In agriculture, this methodology enables a more comprehensive understanding of the dynamic interactions between ecological, social, and economic elements. It critically underscores the interdependencies and cascading effects that alterations in one component of the system can have on others, moving beyond isolating individual factors [51].
- *Visualizing system behavior*: By mapping causal relationships using conceptual models, systems thinking helps visualize reinforcing and balancing feedback loops that drive system behavior [11]. This capability is vital for understanding why certain agricultural practices evolve as they do.
- *Informed decision-making and adaptability*: This comprehensive understanding allows policymakers, farmers, and industry stakeholders to design interventions that promote sustainable agricultural transitions, such as moving from conventional

automation to human–robot collaboration. It fosters adaptable strategies to address the inherent socio-ecological complexities in agriculture.

- *Eliciting mental models and inclusive strategies*: Systems thinking is also important in eliciting mental models that clarify the intricate interconnections between socio-economic systems [51]. The research indicates its role in improving inclusive strategies that harmoniously integrate technological advancements with the values of communities, ensuring that digital innovations are socially accepted and beneficial. This aligns directly with the goal of Responsible Digitalization (Theme 6) to ensure an ethical and inclusive approach, promoting holistic planning.
- *Stakeholder integration*: Incorporating various stakeholder perspectives into the technology assessment process and considering insights that align with stakeholder interests enhances the sustainability of digital agriculture, providing a richer, holistic understanding. It is essential for reaching a rich picture and understanding the holistic interactions in agricultural ecosystems.

In essence, systems thinking moves agricultural analysis from a fragmented view to one that recognizes and leverages the deep interconnections across environmental, social, and economic dimensions, critical for designing truly sustainable and responsible farming practices facilitated by socio-ecological value scorecards.

6 Discussion and implications

The inherent complexity of applying the socio-ecological value scorecard to agricultural ecosystems, as identified by challenges such as system complexity, data ownership concerns, and power imbalances, is a direct manifestation of agriculture as a complex system. Systems thinking approach helps in understanding that interventions in one part of this interconnected system can lead to unintended consequences, highlighting the necessity of evaluating the effects of digital transformation beyond mere productivity improvements. For instance, the risks of digital transformation in agriculture and rural regions when socio-economic and ecological factors are not adequately considered, underscore the need for a holistic assessment of impact [11]. The systemic approach allows for mapping casual relationships and visualizing feedback loops that drive system behavior, crucial for addressing the tension between economic priorities and socio-ecological values. Furthermore, understanding data governance in agricultural systems through a systems lens reveals that obstacles like insufficient access to resources [21, 62], lack of standardization, and concerns over privacy and trust are not isolated issues but rather interconnected challenges within the larger system. The difficulty of adopting digital tools in small-scale farmers can also be better understood by analyzing the systemic barriers, including high costs, digital literacy gaps, and infrastructure limitations, which are often compounded by broader socio-economic factors.

6.1 Identified challenges and gaps

Developing and implementing a socio-ecological value scorecard presents multiple challenges. In our systematic literature review, we found that more research is needed on developing a socio-ecological value scorecard in various ways. Table 9 illustrates the main challenges, and each one is linked to the research questions. The challenges identified—ranging from the inherent tension between economic priorities and broader socio-ecological values, to the complexities of integrating innovative technologies, and critical

Table 9 Identified gaps linked to the research questions

Identified gaps	Research question
Tension between economic priorities and socio-ecological values	RQ5
Complexity of selecting and implementing innovative technologies	RQ4
Align with both short-term and long-term goals	RQ1
Risks of digital transformation in agriculture and rural regions	RQ2
Data governance in agricultural systems	RQ1, RQ2, RQ3
Adopting digital tools in small-scale farms	RQ2

data governance issues—are not isolated. Instead, they represent an interconnected web of complexities inherent to smart agriculture as a diverse and heterogeneous system. Therefore, a holistic approach that considers these interdependencies and draws insights from multiple disciplines, including technology, business, sociology, and ethics, becomes paramount. This integrated perspective is crucial for designing a scorecard that is not only robust in its conceptual framework but also practical and adaptable for future validation in real-world agricultural contexts.

1. *Tension between economic priorities and socio-ecological values*: One of the main issues in developing a socio-ecological value scorecard is balancing easily measurable economic factors with less tangible social and environmental values. Due to financial pressures, the focus shifted to generating income and working with big businesses. The process prioritized quantifiable factors such as CO₂ reduction while overlooking more qualitative aspects of sustainability and innovation. Furthermore, there was a gap between the original goal of supporting farmers and the actual approach, which treats data as a commercial asset [45]. Subscription-based models provide continuous value to farmers and other stakeholders, which are not mentioned.
2. *Complexity of selecting and implementing innovative technologies*: Another challenge is merging technological solutions into various agricultural environments. Innovations like AFSs enhance farm productivity, animal health, and welfare by providing farmers various choices that meet their requirements. When selecting these kinds of innovations, it is essential to consider the feeding technology and the farm practices to guarantee uniform feed distribution, user-friendliness, and dependability. The system must align with the daily activities of farms for optimal system performance. Nevertheless, effective feeding methods remain essential for maintaining animal health and productivity, which influences profitability and sustainability over time [49]. Future research should investigate the customization of these tools for varying farm sizes, species, and resource availability.
3. *Alignment with both short-term and long-term goals*: Developing a scorecard to evaluate the social and environmental impact of virtual herding technologies comes with several challenges related to productivity, environment, land use, and farm management. In the short term, these technologies can lower fencing costs and improve pasture use, but there are still issues with accurately tracking animals, making the best use of forage, and improving health monitoring. In addition, environmental benefits need a better combination with remote sensing and biodiversity efforts. Making sure to follow the environmental regulations and monitoring long-term ecological effects remains a crucial challenge [34]. Comprehensive assessments of ecological sustainability should encompass multi-scale environmental indicators

collected over time, ensuring a holistic evaluation of the health and well-being of the environment.

4. *Risks of digital transformation in agriculture and rural regions*: Digital transformation in agriculture and rural regions must prioritize tackling socio-economic and ecological issues, instead of embracing new technologies [55]. Previous experiences indicate that technology-based changes, when not considering these wider factors, can result in adverse consequences [63, 64]. As a result, when creating a socio-ecological value scorecard, it is essential to evaluate not just technological progress but also its effects on social and environmental frameworks. Ensuring that new agricultural technologies contribute positively necessitates a comprehensive assessment of their impact beyond mere productivity improvements.
5. *Data governance in agricultural systems*: The establishment of strong data governance practices in agricultural systems encounters numerous challenges and prospects. Major challenges consist of insufficient access to vital resources such as sensors, data collection systems, and dependable internet in numerous areas, hindering farmers from embracing and gaining advantages, particularly from smart connected farm networks. Moreover, issues related to data privacy, trust, and the necessity for explicit agreements on data use impede sharing information between farmers. Subsidies, cooperative assistance, and the integration of advanced technologies like AI are policies and strategies that can address these challenges by enhancing the accessibility and usability of data [22]. Also, laws continue to be unclear about the difference between data creation and intellectual property rights in information systems that depend on that data. Alongside ownership issues, privacy concerns emerge, especially because of the vague distinction between commercial farming data and private information [13]. A robust data governance framework can guarantee fair data access, safeguard privacy, and promote collaboration, thereby increasing the value of socio-ecological data in agricultural systems.

For sustainable farming to grow using data, information from many farms needs to be combined. Making good decisions at a larger scale requires lots of data, but farmers are often hesitant to share theirs due to privacy worries and competition. Data can be shared by removing personal details, but this is harder in farming because things like soil types and crop yields can still reveal farm identities [13].

Agricultural data originates from various heterogeneous sources, including machine-generated metrics, remote and proximal sensing, traditional farm records, and human-generated data, including social media. The existing historical documentation on farm data is incomplete and lacks standardization, which is a significant challenge in integrating diverse data sources [13].

6. *Adopting digital tools in small-scale farms*: Barriers such as high costs, digital literacy gaps, and infrastructure limitations must be addressed to make sure that small farmers can effectively adopt these tools. Multi-stakeholder collaboration is essential to create supportive environments that promote affordability, accessibility, and training for farmers. Also, to mitigate the negative environmental effects of digital technologies, upcoming studies should focus on improving energy efficiency in devices and employing renewable energy sources to decrease carbon emissions [32].



Fig. 7 Recommendations for future development of the socio-ecological value scorecard

6.2 Recommendations and future research directions

In this section, we highlight some research ideas and recommendations that researchers can explore when working on developing a socio-ecological value scorecard as shown in Fig. 7.

First, a more *inclusive and comprehensive approach* to developing a socio-ecological value scorecard is necessary to address the identified challenges. The scorecard should integrate broader sustainability measures that account for social, environmental, and economic dimensions. It should also involve all stakeholders in its design and implementation, ensuring that farmers, policymakers, and researchers contribute to defining evaluation measures [45].

Second, the scorecard must be *versatile* for different contexts to provide adaptable solutions that cater to the diverse requirements. Combining scientific techniques with traditional methods can increase sustainable development and social advancement in agriculture [65]. The focus ought to be on creating scalable and accessible approaches for farmers [32]. New technological solutions must consider local internet access, skills of farmers, language preferences, and cultural contexts. This encompasses the development of digital tools aimed at helping agricultural cooperatives in their informed decision-making process [66]. Future research should also investigate the socio-economic factors that affect the willingness of farmers to adopt new technologies and evaluate whether adopters gain a competitive advantage over non-adopters.

Third, it has been determined that the uptake of agricultural automation is driven by two primary forces, which are agribusinesses and rural populations. Farmers are motivated by financial gains, whereas workers prioritize job stability, resulting in opposing views on automation. External influences such as urban development, workforce shortages, and worldwide emergencies could speed up automation. To facilitate adoption, it is crucial to have *clear regulations*, *financial incentives*, and *training programs* that assist both farmers and workers in effectively integrating robotic technologies [51].

Fourth, to effectively utilize IT tools in the agri-food sector, a comprehensive approach is necessary, considering both the business and technological settings and their interaction. IT solutions are more prone to failure when they are not incorporated into the wider agri-food system. Transforming the complete system requires perspectives from various disciplines, including technology, business, sociology, and ethics. Creating a functional ecosystem may require considerable time and resources, and outside assistance, like that from the government, could be essential, particularly as food processing and distribution systems grow increasingly intricate. The structure of these ecosystems ought to encourage *transparency*, *adaptability*, and *equitable cooperation* to achieve the objectives [52]. In particular, the socio-ecological value scorecard should include *broader sustainability measures*, involve all stakeholders, and adopt more participatory evaluation methods to make it more balanced. Furthermore, the methods and measures can be included in a scorecard that aligns innovative technology with equitable and sustainable agricultural practices.

While the SLR does not involve empirical validation of a specific scorecard implementation, its findings significantly enhance the credibility and practical relevance of the socio-ecological value scorecard by grounding its conceptualization in existing research and real-world agricultural challenges. The identification of complexities such as system complexity, data ownership concerns, unintended consequences of digital technologies, degradation of farmer autonomy, and power imbalances ensures the scorecard's design anticipates and addresses practical obstacles, making it more robust. Moreover, the review emphasizes practicality and usability, stressing the need for user-friendly, cost-effective innovations that consider local contexts, internet access, farmer skills, and cultural preferences, particularly for small farmers. This focus on accessibility increases its potential for adoption and effectiveness.

7 Conclusion

This systematic literature review highlights how socio-ecological value scorecards can enhance sustainable smart agriculture through the integration of digital technologies, robust data governance, and systems thinking. While numerous studies have explored and reviewed concepts such as precision agriculture, digital technologies, or sustainability indicators, this study introduces a comprehensive taxonomy of six themes which are sustainability and innovation, data governance and sharing, enabling technologies, digital transformation, new business models, and responsible digitalization. These concepts are utilized to provide a structured lens to understand current research and practical developments, offering a multi-dimensional framework for future research and policy development. Importantly, this review emphasizes the need for adaptable scorecard designs that consider the complexity of agricultural ecosystems, the importance of systems thinking, and the actual experiences of small-holder farmers. By articulating how digital tools and governance practices can be integrated

into a cohesive socio-ecological value scorecard, the study advances the conceptual foundations for developing practical, scalable, and ethically grounded value scorecards.

Our findings show that using new digital technologies together with fair and inclusive practices can substantially improve how agricultural data is used. Moreover, socio-ecological value scorecards emerge as vital tools for assessing environmental, economic, and social performance in complex farming systems. However, their practical deployment requires careful attention to issues such as data privacy, infrastructure disparities, user accessibility for smallholders, and alignment with both short- and long-term sustainability goals.

Although the study conceptualizes the role of socio-ecological scorecards, empirical evaluation and field validation remain areas for future exploration. Future research should also focus on refining data governance frameworks, helping people in rural areas learn digital skills, fostering farmer-centric digital tools, engaging diverse stakeholders in designing and implementing, and promoting responsible digitalization so that socio-ecological value scorecards can serve as a transformative tool to guide stakeholders toward more sustainable, efficient, and ethical agricultural practices by addressing these challenges.

In conclusion, socio-ecological value scorecards offer a promising pathway toward more transparent, inclusive, and sustainable agriculture. Realizing their potential will require not only technical innovation but also strategic governance and participatory design. We believe that the findings of this study will inspire future research aimed at designing and implementing advanced scorecard frameworks, fostering a deeper understanding of their role in optimizing agricultural sustainability and guiding the digital transformation of farming systems.

Author contributions

S.N.: Writing—Review, and Editing, Writing original draft, Methodology, Data Curation, Visualization, Conceptualization
F.D.: Writing—Review, and Editing, Methodology, Visualization, Conceptualization, Supervision
A.M.: Writing—Review, and Editing, Conceptualization.

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Data availability

All data generated or analyzed in this study are included in the article.

Declarations

Ethical approval and consent to participate

We adhere to all ethics as per journal policy.

Clinical trial number

Not applicable.

Consent publication

I consent to publish this article on behalf of all authors.

Competing interests

The authors declare no competing interests.

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