
# Smart Resource Use in Precision Agriculture: A Conceptual Framework for Digital Sustainability Development

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***Abstract***

*Digital and precision agriculture are expected to play a central role in shaping future sustainable food production systems by enabling more intelligent, adaptive, and resource-efficient processes. This study adopted a literature review, composed of bibliometric and systematic aspects, to propose a conceptual framework for Smart Resource Use as an emerging paradigm for sustainable development in digitally enabled precision agriculture, extending the concept of smart consumption beyond its traditional origins in digital manufacturing. This study examined how next-generation technologies can progressively transform the management of critical agricultural resources such as water, energy, soil, and inputs. Our analysis included a conceptual synthesis of recent advances in digital agriculture, including remote sensing, artificial intelligence, machine learning, automation, robotics, big data analytics, decision support systems, and agricultural digital twins. It indicated that agricultural systems are moving beyond efficiency-based approaches towards predictive, autonomous, integrated, and system-level resource management models capable of dynamically allocating resources at field and sub-field scales, reducing environmental impacts, and enhancing resilience to climate variability. A shift from only maximizing yield to improving resource-use efficiency and long-term sustainability outcomes was also observed. From a sustainability perspective, the Smart Resource Use paradigm is positioned as a key enabler of the United Nations Sustainable Development Goals, particularly SDG 2 by supporting long-term food security and productivity growth, SDG 6 through advanced water-use optimization, SDG 12 by minimizing input waste and promoting circular resource use, and SDG 13 by enabling climate-smart and low-carbon agricultural practices. As a contribution to future research, the conceptual framework presented could be used as a basis to strategically plan the transition toward digitally enabled sustainable agricultural systems. It also provides strategic insights for researchers, policymakers, and practitioners seeking to design the next generation of resource-efficient agricultural solutions. Lastly, the main research gaps observed in the current literature and practice in the relevant areas analyzed were also described.*

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# Introduction

Agricultural systems are increasingly required to increase yield while improving resource use efficiency, lowering environmental impacts, and adapting to climate variability. Water scarcity, soil degradation, increasing energy demand, inefficient input use, and climate-related production risks have intensified the need for agricultural models that move beyond yield maximization alone. In this context, sustainability in agriculture depends on improving how critical resources are monitored, allocated, and used across spatial and temporal scales. Digital agriculture has therefore become central to the design of more sustainable agricultural systems, as it enables new forms of data-driven planning, monitoring, and management (Basso & Antle, 2020).

Precision agriculture and digital technologies have long contributed to more accurate observation and management of field spatial variability. Remote sensing, for example, has played a significant role in precision agriculture by supporting spatially-aware crop monitoring, soil and water assessment at scale. However, important knowledge gaps remain regarding the integration, adoption, and operational use of its techniques and tools. More recently, the expansion of smart farming has intensified this transformation by connecting sensors, machines, data platforms, decision-support tools, and automated systems into more integrated farm management environments. Smart farming techniques and tools enable agricultural systems to collect, process, and interpret large volumes of heterogeneous data, creating opportunities for more adaptive, predictive, and resource-efficient food production systems (Wolfert et al., 2017; Liakos et al., 2018).

Considering this perspective, the relationship between digital transformation and sustainability has been increasingly associated with environmental innovation. Digital transformation and environmental innovation can jointly support sustainability by improving resource efficiency, reducing environmental impacts, and enabling resilient economic and production systems (Pricopoaia et al., 2025). In agriculture, this relationship is particularly relevant because digital technologies can support climate adaptation, resource optimization, and food security through innovations in precision agriculture, smart farming, and data analytics. From a strategic management perspective, the Resource-Based View (RBV) provides a useful lens for understanding how agricultural organizations develop competitive advantage through valuable, rare, inimitable, and organizationally embedded resources and capabilities (Barney, 1991). In digital agriculture, these resources may include data infrastructures, analytical capabilities, digital platforms, technological expertise, and decision-making routines. However, because agricultural production is strongly dependent on natural resources, the Natural Resource-Based View (NRBV) extends this logic by emphasizing environmental capabilities, pollution prevention, product stewardship, sustainable development, and the strategic management of natural resources (Hart, 1995). Together, RBV and NRBV suggest that digital transformation in agriculture should be understood as a process of combining digital resources, organizational capabilities, and environmental resources to generate sustainable systems.

Recent studies point out that digital transformation can enhance sustainable performance in agricultural supply chains. Digital maturity has been associated with improved sustainable performance in agri-food supply chains, particularly by strengthening coordination, responsiveness, and operational capabilities (Barbosa et al., 2025). Digital transformation has also been identified as a pathway for improving sustainable supply chain performance in agricultural contexts, including better information flows, technological integration, and process optimization (Li et al., 2025; Marcone, 2025). In agribusiness, digital technologies can support sustainable operations by improving efficiency, decision-making, and resource management across production and supply chain activities (Wang et al., 2025).

Although several studies report positive associations between digital transformation and sustainability performance, the mechanisms through which digital technologies generate sustainability outcomes remain insufficiently explained. Studies on the Internet of Things (IoT) paradigm and data analytics show their potential to improve resource efficiency and crop productivity, especially in smallholder agriculture, while pointing to persistent challenges related to infrastructure, data use, and adoption capacity (Hope & Mwebaze, 2025). Research on Artificial Intelligence (AI), Machine Learning (ML), big data, and green supply chains similarly highlights opportunities for sustainability-oriented innovation, resilience, and disruption management, while emphasizing barriers associated with technological adoption, governance, and organizational readiness (Nayal et al., 2023). In parallel, eco-innovation has been shown to contribute to agricultural sustainability, suggesting that environmental performance depends on the capacity to transform technological and organizational innovation into concrete sustainability practices (Buchana, 2025).

These gaps indicate the need for a more integrated conceptual perspective on digital agriculture and resource management. In particular, existing studies often examine specific technologies or isolated efficiency gains, while fewer studies explain how digital tools can be combined into broader capabilities for sustainable resource use. This gap is especially relevant for agricultural systems, where water, soil, energy, nutrients, and inputs are interconnected and must be managed under uncertainty, spatial variability, and climate risks. A conceptual framework could be useful in this context to help organize dispersed concepts, clarify relationships among constructs, and support theory development in emerging research fields (Jabareen, 2009).

To address this gap, this paper proposes Smart Resource Use as an emerging paradigm for digitally enabled sustainable agriculture. Smart Resource Use refers to the capacity of agricultural systems to combine digital technologies, natural resource management, and resource-oriented decision-making to improve the efficiency, adaptability, and sustainability of resource allocation. Rather than treating digital tools as isolated technological solutions, this perspective emphasizes their role in supporting integrated resource management, circular use of inputs, climate-smart practices, and system-level optimization. This study adopts a literature review, combining bibliometric and systematic elements, to examine how current digital technologies contribute to Smart Resource Use in precision agriculture.

# Framework for Smart Resource Use in Smart Farming

Based on the works by Wolfert et al. (2017), Barney (1991), Pricopoaia et al. (2025), Hart (1995), Hope and Mwebaze (2025), and Buchana (2025), we propose a conceptual framework for applying NRBV and Smart Resource Use, together with Smart Farming tools, techniques, and technologies, to improve the sustainability outcomes of food production systems, with an emphasis on on-farm processes and activities. Figure 1 illustrates the proposed framework. It is based on a conceptual synthesis approach.

The framework was constructed by identifying, organizing, and integrating the main concepts, technologies, capabilities, and sustainability outcomes emerging from the literature on digital agriculture and smart farming. This procedure followed the conceptual framework development principles proposed by Jabareen (2009), which recommend the extraction, categorization, and synthesis of key constructs from multidisciplinary literature into a coherent explanatory structure.

The analyses conducted focused on how digital technologies can support the management of critical agricultural resources such as water, energy, soil, nutrients, and production inputs. By synthesizing these research streams, the paper develops a conceptual framework for understanding how digital agriculture can support the transition from efficiency-based practices to intelligent, predictive, adaptive, and sustainability-oriented resource management.

The analyses focused on four complementary themes: (i) smart farming, automation, robotics, and AI; (ii) remote sensing; (iii) resource-based view; and (iv) virtual reality (VR) and digital twins.

These themes were selected because they consistently emerged as major technological and conceptual domains across the reviewed literature and collectively encompass sensing, decision-making, automation, simulation, and sustainability-oriented resource management capabilities. Together, these themes provided the foundation for identifying key capabilities, technologies, and sustainability outcomes associated with digitally enabled agricultural systems that are critical to develop sustainable farming systems considering the current agricultural practices and food demands.

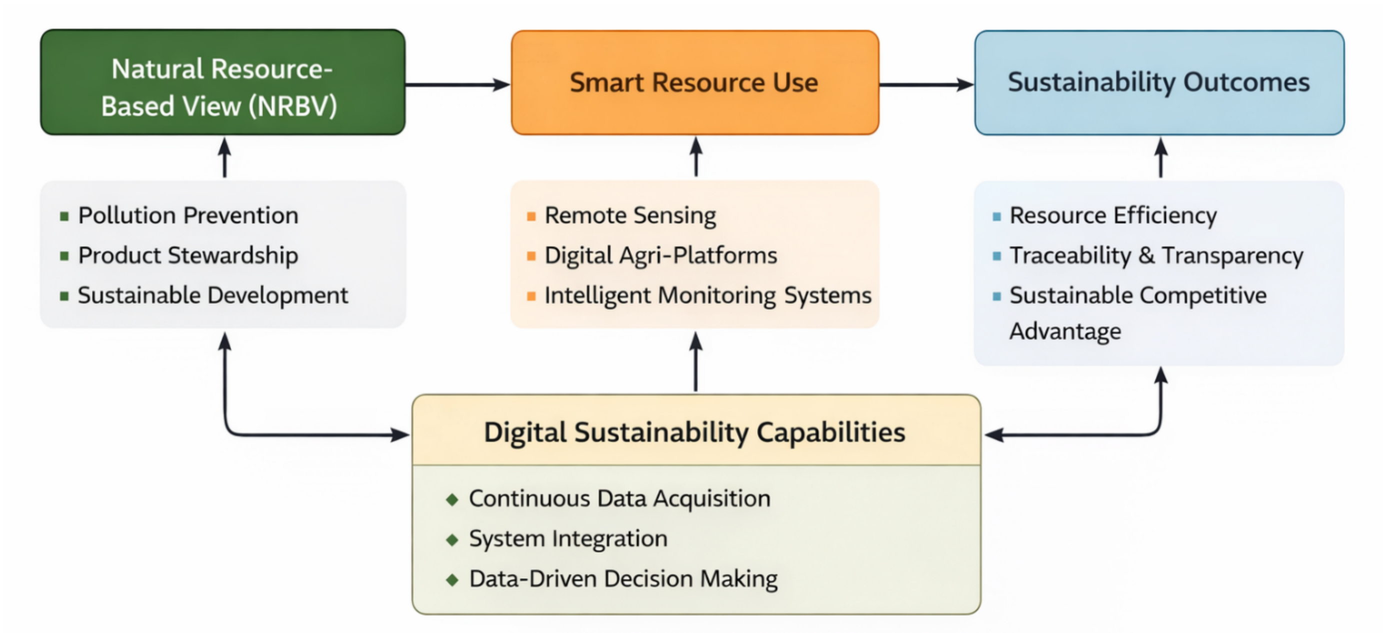


Figure 1 . Conceptual Framework proposed.

# Methodology

The methodology used in this paper was composed of four main steps. In the first step, the main relevant technologies were identified, based on an extensive analysis of the main literature reviews on digital agriculture, including the works of Wolfert et al. (2017), Dhal et al. (2024), Akkem et al. (2023), Idoje et al. (2021), and Roy and Medhekar (2025). The NRBV was considered to identify technologies that both impacted on the production system itself and on its resource use and potential environmental and social impacts.

The second step was to divide the technologies into groups, based on their characteristics, contexts, and applications at on-farm activities and processes. Four groups were identified: smart farming, automation, robotics, and AI; remote sensing; RBV and NRBV; and VR and digital twins. These will be addressed individually in the Results and Discussions section.

The third step was to conduct an extensive literature review on the applications of the technologies, tools, and techniques in each group identified in the previous step for smart farming and digital agriculture. Different time periods were used for each group because the topics differ in their level of technological maturity and adoption, and rate of technological progress. More established fields were analyzed over longer periods, while emerging topics were examined using more recent literature to capture the latest advances and trends.

Therefore, a bibliometric review was conducted for the smart farming, automation, robotics, and

AI, remote sensing, and RBV and NRBV groups. The steps for conducting the reviews were based on the works by Rejeb et al. (2022) and Rasera et al. (2023), and encompassed: (i) string search definition based on a traditional systematic literature review; (ii) data collection from the Scopus database; (iii) data filtering; (iv) paper screening based on pre-defined exclusion criteria; and (v) knowledge extraction and analysis using the tools and techniques available on the Bibliometrix package (Aria and Cuccurullo, 2017).

Each subsection on the Results and Discussions section will contain the further descriptions of each step for the specific group. In the case of the VR and digital twins group, as it is a field that is less mature in terms of applications for smart farming and digital agriculture, a structured literature review inspired by PRISMA guidelines (Page et al., 2021) was adopted. On the screening step, papers that were not related to smart farming or digital agriculture, or that did not address the specific technologies, techniques, and tools of the specific group were excluded. Screening was performed through title and abstract evaluation according to predefined inclusion and exclusion criteria.

# Results and Discussions

### Smart Farming, Automation, Robotics, and AI

For the analysis of the main technologies related to this group applied to modern farming systems, the following search string was used: ( "digital agriculture" OR "smart farming" OR "smart farm" ) AND ( automation OR "artificial intelligence" OR "machine learning" ). The results were filtered between 2010 and 2025. This resulted in 5.671 documents. Then, filters on document type (only conference papers and journal articles, resulting in 4.493 documents) and language (only English, resulting in 4.400 documents) were applied. Lastly, the top 200 most cited papers were selected for the title and abstract screening process. The screening resulted in 122 documents, which were then evaluated.

The final analysis encompassed 122 documents, from 2014 until 2024. It was observed an increasing number of citations over the analyzed period, which may be associated with several factors: (i) the increasing development and application of deep learning methods (especially convolutional neural networks) from 2015 onwards, like in the works of Lottes et al. (2017) and Sharma et al. (2024); (ii) the increasing availability of low-cost and high quality sensors (Muangprathub et al., 2019; Shahab et al., 2025); and (iii) the development of open software and implementations of deep learning models. It is important to observe that data collection was also increasingly present from 2018 onwards, due to the implementation of systems considering the IoT paradigm, such as the works of Muangprathub et al. (2019) and Shahab et al. (2025).

The most important sources identified were: Computers and Electronics in Agriculture (11% of the documents), IEEE Access (7% of the documents), and IEEE Internet of Things Journal and Smart Agricultural Technology (each with 3% of the documents). This is an interesting result: while Computers and Electronics in Agriculture and Smart Agricultural Technology are domain-specific, the other two sources (IEEE Access and IEEE IoT Journal) are domain agnostic, and the papers in the dataset belonging to latter ones are IoT-related. This points out to the importance of considering the IoT paradigm in the agricultural sector, for several reasons (Muangprathub et al, 2019; Shahab et al., 2025; Alonso et al., 2020; Kassim, 2020): energy-saving purposes, the amount of data generated, heterogeneous datasets, an increase in the amount of data nodes, among others.

It is interesting to observe that the main countries in terms of citations were: India, Australia, China, and Italy. Evaluating the papers, they present distinct concerns. The analyzed publications suggest that India has shown particular interest in IoT and low-cost systems, whereas Australian studies frequently addressed high-yield production systems. This illustrates different infrastructure as well as distinct production systems and relevant crops.

The main keywords in the papers analyzed can be classified in two main categories: agriculture-related, and technology-focused keywords. The first contains terms such as: smart farming, precision agriculture, agricultural robots, crops, digital agriculture, soil moisture, crop yield, and irrigation. The second one points out to the main technologies used to collect data, extract knowledge, improve decision-making, and automate processes, encompassing: IoT, machine learning, deep learning, sensors, convolutional neural networks, artificial intelligence, wireless sensor networks, and learning systems. Those results can be summarized in two main observations (Wolfert et al., 2017; Rejeb et al., 2022; Akkem et al., 2023; Idoje et al., 2021; Dhal et al., 2024; Roy, Medhekar, 2025): (i) different technologies are being used in agriculture for different processes, activities, and with complementary objectives; and (ii) the agricultural sector is adopting state-of-the-art technologies for knowledge extraction and automation, considering heterogeneous data.

The increasing use of sensors and the infrastructure and systems related to its use in the agricultural sector demanded more organized processes to deal with the data generated, and IoT is a paradigm that addresses this problem (Shahab et al., 2025; Kassim, 2020). The basic themes of the majority of papers considered precision agriculture, IoT, machine learning and deep learning, and agricultural robots, reinforcing the observation that the agricultural sector is investing in developing and implementing state-of-the-art technologies to improve its production processes (Wolfert et al., 2017; Akkem et al., 2023; Roy, Medhekar, 2025).

### Remote Sensing for Smart Resource Use in Digital Agriculture

For this group, the search string adopted was: "remote sensing") AND ("resource use efficiency" OR "resource management" OR optimization OR "decision support" OR irrigation OR nutrient*) AND (agriculture OR farming OR "precision agriculture" OR "digital agriculture"). The initial search returned 6,025 documents. After applying a temporal filter covering the period from 2010 to 2024, the dataset was reduced to 4,798 publications. Subsequently, only articles, review papers, and conference papers were retained, resulting in 4,305 documents. Finally, the language filter was restricted to English, yielding a final dataset of 3,971 eligible publications. From this set, the 100 most cited documents were exported and analyzed.

The analyzed corpus comprised publications distributed across 57 scientific sources and produced by 583 authors. The dataset contained 11,379 cited references and presented an average of 6.13 co-authors per document, indicating a high degree of scientific collaboration. International collaboration accounted for 39% of the publications, reinforcing the global nature of research related to digital agriculture and sustainable resource management. The selected corpus exhibited a high scientific impact, with an average of 349.4 citations per document.

The temporal distribution of publications reveals the growing importance of remote sensing for agricultural resource management over the last decade. Although the analyzed corpus spans the period between 2010 and 2024, a substantial concentration of highly cited publications emerged after 2020. The year 2021 presented the highest number of publications within the selected corpus, with 18 documents, followed by 2020 and 2022, with 11 and 9 publications, respectively. This trend suggests an increasing scientific interest in the application of remote sensing technologies to support digital agriculture and sustainable resource management.

The most productive scientific sources were Remote Sensing (11 documents), Remote Sensing of Environment (8 documents), Computers and Electronics in Agriculture (7 documents), and Science of the Total Environment (6 documents). Other relevant journals included ISPRS Journal of Photogrammetry and Remote Sensing, Precision Agriculture, and Agricultural Water

Management. The predominance of these sources demonstrates the strong connection between remote sensing research and agricultural, environmental, and geospatial sciences.

From a geographical perspective, the United States emerged as the leading contributor, followed by China and India. Significant participation was also observed across Europe, Oceania, and emerging agricultural economies. The geographical distribution of publications highlights the global relevance of remote sensing technologies for addressing challenges related to agricultural productivity, climate adaptation, environmental monitoring, and sustainable resource management.

The thematic analysis revealed four major research domains. The first domain is associated with water-resource management, encompassing irrigation, soil moisture monitoring, evapotranspiration, drought assessment, and water-use efficiency. The second domain focuses on precision agriculture and crop monitoring, including crop assessment, yield estimation, and site-specific management practices. A third domain addresses environmental monitoring and climate adaptation, emphasizing land-use dynamics, climate change, and sustainability challenges. Finally, a fourth domain reflects the growing integration of remote sensing with data-driven decision-support approaches, including ML, AI, image processing, and automation.

The thematic evolution analysis indicates a gradual transition from traditional monitoring-oriented studies toward more advanced digital agriculture approaches. Earlier studies were primarily centered on agricultural production, irrigation, image processing, and remote sensing applications. More recent publications increasingly incorporate climate-related analyses, satellite data, ML techniques, and decision-support systems, reflecting the ongoing digital transformation of agricultural management.

Despite the maturity of several research streams, important gaps remain. The current literature is strongly concentrated on monitoring and assessment applications, particularly those associated with water-resource management. In contrast, topics such as nutrient-use efficiency, integrated resource optimization, sensor fusion, digital twins, interoperability, and autonomous decision-support systems do not emerge as dominant research themes within the analyzed corpus. Likewise, although AI and ML are becoming increasingly relevant, their integration into broader frameworks for intelligent and adaptive resource management remains limited.

The results also indicate a transition toward the concept of Smart Resource Use, driven by the integration of remote sensing, IoT, AI, and digital platforms. Although monitoring applications still dominate the literature, recent trends point toward more intelligent and adaptive systems capable of transforming data into real-time recommendations and management actions. These developments have the potential to improve productivity, resource-use efficiency, and sustainability simultaneously (Lowenberg-DeBoer & Erickson, 2019; Basso & Antle, 2020).

### Resource-Based View and Natural Resource-Based View

For the RBV and NRBV group, two complementary searches were conducted to better encompass the relevant literature. The first was broad and exploratory in nature, while the second was more restrictive and theoretically oriented. The first string used was: (“natural” OR RBV OR NRBV) AND (“digital” OR “digital transformation”) AND sustainab* AND agricultur*. This initial search returned 758 documents. After applying the temporal filter, considering the period from 2010 to 2025, the set was reduced to 638 documents. Next, only scientific articles and conference papers were retained, resulting in 475 documents. Finally, the language filter restricted the sample to publications in English, totaling 435 eligible documents. From this set, a corpus of the 100 most cited documents exported from Scopus was analyzed.

Based on the thematic analysis, it was observed that the first search predominantly retrieved technical-environmental literature. The studies were organized around four major axes:

geospatial technologies and environmental monitoring; sustainability, natural resources, and agricultural development; Agriculture 4.0, smart farming, and the IoT; and biodiversity, digital agriculture, and ecosystem services. These clusters show that digital transformation in agriculture has been analyzed mainly as an instrument for environmental monitoring, productive efficiency, conservation of natural resources, soil management, food security, and adaptation to climate change. However, the preliminary analysis also indicated that terms directly associated with RBV and NRBV did not appear prominently in the corpus. This suggested that the term “natural,” present in the first string, broadened the scope of the search, retrieving studies on natural resources, ecosystems, and environmental conservation, but not necessarily studies grounded in strategic theories of resources and capabilities.

Based on this finding, a second, more refined and theoretically oriented search was conducted. The second string was: (“resource-based view” OR RBV OR “natural resource-based view” OR NRBV) AND (“digital transformation” OR digitalization OR digitalisation OR “digital technology” OR “digital technologies” OR “digital agriculture” OR “smart farming” OR “agriculture 4.0” OR “precision agriculture”) AND (sustainability OR sustainable OR “sustainable development”) AND (agriculture OR agricultural OR agribusiness OR farming). This search initially returned 14 documents. The temporal filter from 2010 to 2025 retained all 14 documents. After applying the document-type filter, considering only articles and conference papers, the set was reduced to 8 documents. The language filter, restricted to publications in English, maintained the same 8 documents. Thus, the second search resulted in a refined subcorpus of 8 documents.

The indicators from the second search reveal a still incipient literature. The refined subcorpus consisted of documents published between 2021 and 2025, distributed across 8 distinct sources. A total of 24 unique authors were identified, with an average of 3 authors per document. Of the 8 documents, 6 were articles and 2 were conference papers. All documents from the second search were published between 2020 and 2025, with 7 of them in 2025 and 1 in 2021. China was the country with the highest production, with 2 documents.

The comparison between the two searches reveals an important contrast. While the first string initially retrieved 758 documents and 435 after the filters, the second string returned only 14 documents initially and 8 after the filters. This reduction shows that there is a growing body of research on digital transformation, agriculture, and sustainability, but few studies explicitly articulate this discussion with the RBV and NRBV approaches. In other words, the broader literature has advanced in analyzing the role of digital technologies in promoting agricultural sustainability, productive efficiency, traceability, environmental monitoring, and conservation of natural resources, but there is still limited integration with strategic theories on resources, organizational capabilities, environmental capabilities, and sustainable competitive advantage.

Overall, the results indicate that the literature on digital agriculture and sustainability is expanding, interdisciplinary in nature, and strongly oriented toward technical-environmental issues. However, the specific intersection between digital transformation, agricultural sustainability, and RBV/NRBV remains limited. This gap justifies the relevance of the present study, as it suggests the need to integrate the literature on digital technologies applied to agriculture with strategic perspectives based on resources and capabilities. Thus, digital transformation in agribusiness can be understood not only as the adoption of technologies, but as a process of developing, combining, and exploiting digital and environmental resources capable of generating sustainable performance and competitive advantage.

String 2 literature suggests that digital transformation is increasingly positioned as a strategic pathway for improving sustainability in agri-food and agricultural supply chains, particularly through technologies such as IoT, data analytics, AI, big data, smart farming, and digital maturity capabilities. Empirical studies show that digital transformation can enhance sustainable supply chain performance by improving coordination, operational efficiency, innovation capacity, resource management, and responsiveness across agri-food systems (Li, Panichakarn, & Xing, 2025; Barbosa et al., 2025; Wang et al., 2025; Marcone, 2025).

Despite this growing body of research, important gaps remain regarding the mechanisms through which digital technologies are converted into measurable sustainability outcomes, especially in emerging economies, smallholder farming contexts, and supply chains with uneven levels of digital readiness (Barbosa et al., 2025; Hope & Mwebaze, 2025). In addition, although Agriculture 4.0 and smart farming are recognized as important for scaling innovation and strengthening farmer capabilities, the literature still provides limited longitudinal and comparative evidence on how these capabilities evolve and influence sustainable business performance over time (Kumar et al., 2021).

### Virtual Reality and Immersive Analytics for Smart Resource Use in Agriculture

In this group, a structured literature review inspired by PRISMA guidelines was conducted to investigate how Virtual Reality has been applied to support sustainable agriculture, smart resource management, decision support, digital twins, and agricultural training. The search was conducted in the Google Scholar database considering publications between 2020 and 2026. Only peer-reviewed journal articles and conference papers written in English were considered. The search strategy combined terms related to Virtual Reality and digital agriculture as follows:

**Query 1**: ("virtual reality" OR VR OR "immersive environment") AND (agriculture OR farming OR "precision agriculture" OR "digital agriculture")

**Query 2:** ("virtual reality" OR VR OR "immersive environment") AND (agriculture OR farming OR "precision agriculture") AND "decision"

The role of VR in agriculture extends beyond visualization, providing immersive environments where users can interact with virtual representations of crops, soil, machinery, livestock, and entire farming ecosystems. VR constitutes one of the main components of Extended Reality (XR), enabling users to interact with fully virtual environments through head-mounted displays, motion-tracking systems, and immersive interfaces. Recent reviews indicate that XR technologies have significant potential to address modern agricultural challenges by improving training, operational planning, remote collaboration, and human–machine interaction (Anastasiou et al., 2023).

The integration of VR with precision agriculture technologies has further expanded its potential applications. By incorporating data from sensors, drones, remote sensing, and IoT, VR environments enable users to visualize and analyze agricultural conditions in three-dimensional space. These capabilities facilitate the interpretation of spatially distributed variables such as crop health, soil conditions, irrigation requirements, and pest infestations. VR-based systems can support crop management through immersive simulations, virtual scouting, data visualization dashboards, and scenario testing, thereby assisting farmers in evaluating alternative management strategies before implementing them in the farm (Kaya, 2025).

Another important development is the convergence between VR and Digital Twin technologies. Digital Twins create virtual replicas of agricultural assets, processes, and environments by integrating real-time information from sensors, weather stations, satellite observations, and IoT devices. These systems enable the simulation and prediction of agricultural scenarios while supporting the optimization of irrigation, fertilization, pest management, and resource allocation strategies. VR serves as an intuitive visualization and interaction layer, allowing stakeholders to explore Digital Twins in immersive environments and gain a deeper understanding of complex agricultural systems (Peladarinos et al., 2023). Such capabilities are particularly valuable for resource-intensive decisions involving irrigation scheduling, fertilization management, pest control, and crop planning.

Furthermore, immersive technologies facilitate collaborative decision-making among farmers, agronomists, researchers, and policymakers. Shared virtual environments enable stakeholders to collectively analyze agricultural scenarios, discuss alternatives, and evaluate potential interventions within a common digital workspace. Such collaborative approaches can improve communication, knowledge transfer, and consensus-building, particularly in complex agricultural systems where decisions involve multiple actors and objectives (Spyrou et al., 2025).

Despite its potential, the integration of VR and Digital Twins still faces challenges related to interoperability, scalability, real-time data synchronization, and validation in operational agricultural settings. Further research is needed to develop robust frameworks capable of supporting large-scale deployment and demonstrating practical benefits for agricultural stakeholders (Peladarinos et al., 2023; Liu et al., 2024).

## Detailed Framework Addressing the Main Opportunities Identified

Considering the main aspects, gaps, and opportunities identified in the analysis conducted in the last subsections, we propose a detailed description of the conceptual framework for understanding how digital technologies can support sustainability in precision agriculture, digital agriculture, and smart farming. As illustrated in Figure 2, it is grounded in the RBV and the NRBV paradigms. The RBV can help explain how valuable digital resources and organizational capabilities can contribute to sustainable competitive advantage, while NRBV extends this perspective by emphasizing natural resource stewardship, pollution prevention, sustainable development, and long-term value creation. Together, these perspectives suggest that sustainable agricultural performance depends on the effective combination of natural resources, digital resources, and organizational capabilities.

The proposed framework shows that Smart Resource Use in digital agriculture is enabled by a set of interrelated technologies, particularly remote sensing, smart farming systems, VR, digital twins, AI, digital platforms, and intelligent monitoring systems. Remote sensing plays a key role in monitoring crops, water, soil, and spatial variability, supporting more precise and timely decisions. Smart farming expands this potential by integrating sensors, digital platforms, automation, data analytics, and decision-support systems into connected farm management environments. In parallel, VR and digital twins introduce new possibilities for simulation, visualization, immersive decision support, and scenario analysis, allowing agricultural actors to evaluate actions and optimize resource use before implementation in real production settings.

However, the value of these technologies is not automatic. Their contribution to sustainability depends on the development of digital sustainability capabilities, such as continuous data acquisition, system integration, data-driven decision-making, adaptive learning, interoperability, governance, and data quality. These capabilities act as the central connecting element in the framework, linking the technological base of smart farming and digital agriculture to sustainability-oriented resource management. In this sense, digital sustainability capabilities transform data and technological infrastructures into actionable knowledge that can improve irrigation, nutrient management, energy use, traceability, and broader farm-level and supply-chain decisions. This opens an important agenda for future quantitative research.

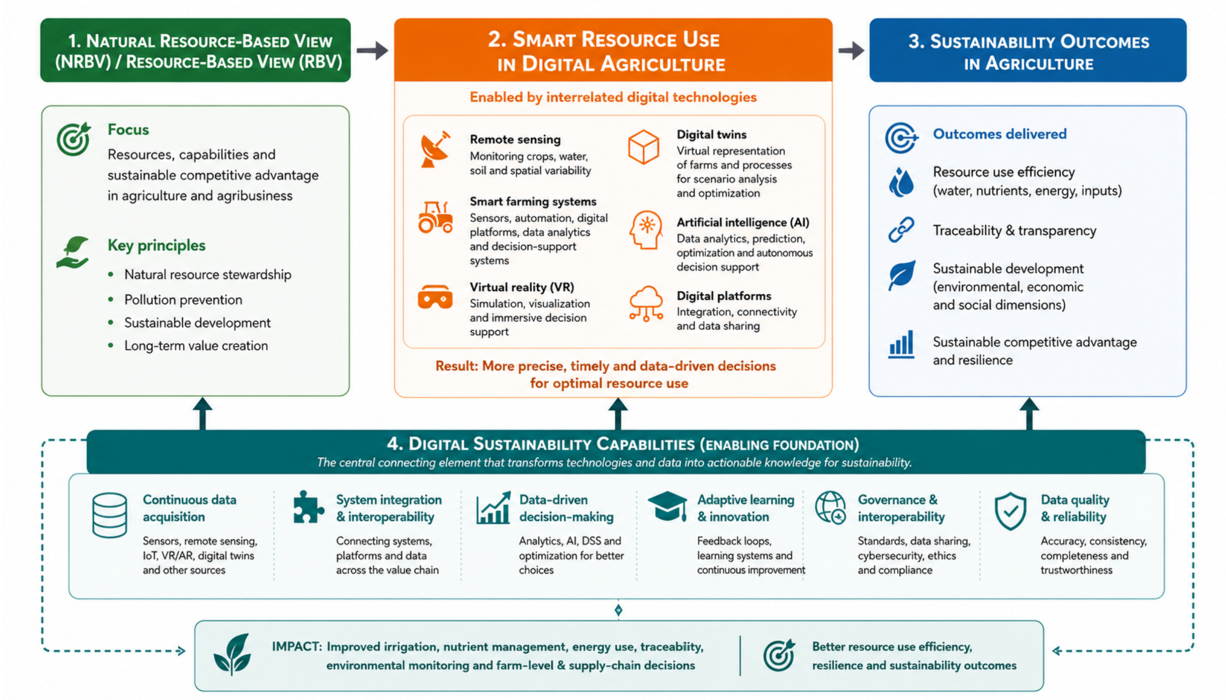


Figure 2. Conceptual Framework of Smart Resource Use in Digital Agriculture.

As smart farms generate more data, there is an increasing demand for storage space and computation to process and extract knowledge from this data. Figure 3 illustrates this aspect for the 2021-2025 period, demonstrating that cloud and network architecture became basic themes in this period. Of specific interest for the current paper, sustainable development appeared as a niche theme, confirming the hypothesis that the agricultural sector has increased its concern with sustainability, environmental impacts, and resource use efficiency in the last years (Sharma et al., 2020; Sott et al., 2020; Wolfert et al., 2017). Lastly, big data and data set appear as emerging themes on the latter period, pointing out to two interesting aspects: (i) the increasing availability of open datasets that can be used for model training and knowledge extraction; and (ii) the need to adopt big data related processing and storage techniques and systems.

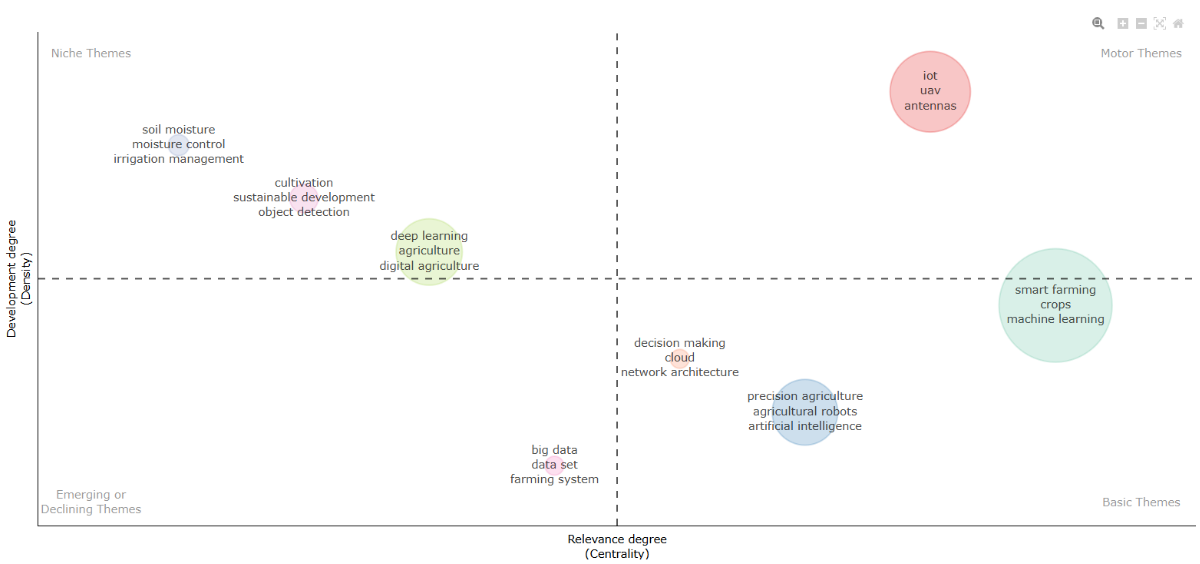

Figure 3. Thematic evolution analysis for the period of 2021-2025.

The proposed framework also reinforces the importance of connecting digital agriculture with the principles of the NRBV. Pollution prevention, sustainable development, and long-term value creation remain central to the transition toward more sustainable agricultural systems. When these principles are combined with digital sustainability capabilities and advanced technologies such as remote sensing, VR, and digital twins, they can support a more strategic and integrated use of water, nutrients, energy, soil, and agricultural inputs. Thus, Smart Resource Use provides a conceptual pathway for moving beyond efficiency-oriented approaches toward predictive, adaptive, circular, and system-level resource management.

From a sustainability perspective, Figure 2 highlights that Smart Resource Use can generate multiple outcomes, including resource-use efficiency, traceability and transparency, sustainable development, resilience, and sustainable competitive advantage. These outcomes are particularly relevant in agricultural systems facing climate variability, resource scarcity, environmental pressure, and rising food security demands. By integrating smart farming technologies and resource-oriented strategies, agricultural systems can become more capable of reducing waste, improving input allocation, supporting climate-smart practices, and strengthening long-term sustainability performance.

The evidence base derived from the bibliometric and systematic searches supports the relevance of this framework by showing that several research streams are converging around digital transformation, sustainability, remote sensing, smart farming, VR, decision support, and digital twins. Nevertheless, important gaps remain. The literature is still fragmented across technological domains, and there is limited integration between RBV/NRBV perspectives, digital agriculture, and measurable sustainability outcomes. More research is therefore needed to explain how digital technologies are transformed into organizational and operational capabilities, how these capabilities affect resource-use efficiency, and under what conditions they generate sustainability benefits across different farming systems, regions, and agri-food supply chains.

As a contribution to future research, this paper offers a conceptual basis for investigating Smart Resource Use as a multidimensional construct in digital agriculture. Future studies may operationalize the framework empirically, test the relationships among RBV- and NRBV-related resources, digital sustainability capabilities, and sustainability outcomes, and compare different agricultural contexts, including smallholder farming, large-scale commercial farming, controlled-environment agriculture, and agri-food supply chains. Further research should also explore issues related to technology accessibility, interoperability, data governance, farmer capability development, and the broader social and economic implications of digital resource management.

## Conclusions

As explored throughout this paper, digital agriculture and smart farming technologies are increasingly being adopted on modern food production systems. These encompass diverse technologies, from sensing, to data extraction and decision-making to actuation. We conducted extensive literature reviews on four major groups of techniques, tools, and technologies that can be applied in this context to improve the systems sustainability, efficiency, and yield.

The analyses used bibliometric and systematic literature review tools and techniques. Then, a conceptual framework was proposed and described to incorporate the RBV and NRBV paradigms to improve production systems and to implement Smart Resource Use concepts and techniques, leading to more sustainable practices. Strategic, technical, and operational aspects were considered, with an on-farm perspective. We aimed to provide an overview of how those technologies, techniques, and tools could be used, in the context of a conceptual framework, to develop more sustainable and efficient food production systems.

In practical terms, the framework provides guidance for researchers, policymakers, technology developers, and agricultural practitioners seeking to design more sustainable digital agriculture strategies. The framework highlights the relevance of investments in data infrastructures, remote sensing applications, smart farming platforms, interoperable systems, digital twin and VR-based tools, farmer training, governance mechanisms, and policy incentives that enable the responsible and effective use of digital technologies. By doing so, Smart Resource Use can support the transition toward agricultural systems that are more efficient, transparent, resilient, and aligned with long-term sustainability goals, including SDG 2, SDG 6, SDG 12, and SDG 13.

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