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Research Article

Mapping Agricultural Technology Innovation Research for Food Security: A Bibliometric Approach

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Abstract
This study aims to map the development of agricultural technology innovation research in supporting food security using a bibliometric approach. The analysis was conducted on a dataset of scientific publications indexed in selected academic databases during the period 2015–2025, serving as the unit of analysis to identify conceptual structures, thematic clusters, research evolution, and emerging research gaps. The keyword visualisation results show the dominance of the themes of precision agriculture, artificial intelligence (AI), the Internet of Things (IoT), smart farming, and digital agriculture as the main drivers of the transformation of modern agricultural systems. The cluster map shows a close relationship between technological innovation, sustainability, and food security, while the density–centrality analysis places precision agriculture and digital agriculture as motor themes with high centrality and density. Thematic evolution shows a shift from the conservation and sustainability paradigm towards data-based and artificial intelligence-based agricultural systems integrated with digital governance and the circular economy. Although technology is the dominant focus, aspects of farmer adoption, governance, digital inclusion, and policy integration remain strategic research gaps. These findings confirm that the transformation of agriculture towards a resilient food system requires multidisciplinary integration between technological innovation, environmental sustainability, and institutional and public policy support.

Keywords: Agricultural Technology Innovation, Artificial Intelligence, Digital Agriculture, Food Security, Precision Agriculture

1. Introduction

Food security has become a strategic global issue in line with population growth, climate change, natural resource degradation, and disruption of the food supply chain. These challenges demand the transformation of the agricultural system from a conventional approach to a more productive, efficient, and sustainable system. The concept of Climate-Smart Agriculture as proposed by Sapkota (2015) emphasising the importance of integrating climate change adaptation, greenhouse gas emission mitigation, and productivity enhancement simultaneously. Meanwhile, agroecological approaches and sustainable intensification are also seen as strategies to bridge the production gap without expanding agricultural land, as discussed by Ewert (2023). Thus, agricultural technology innovation is a key instrument in ensuring long-term food availability, accessibility and stability.

The development of digital technology has led to the emergence of precision agriculture, which integrates sensors, decision support systems and data analytics to improve input efficiency and production yields. According to Finger (2019), Precision agriculture plays an important role in optimising the use of fertilisers, water and energy while minimising environmental impact. Furthermore, the adoption of the Internet of Things (IoT) and smart farming architecture enables real-time monitoring of land conditions, thereby improving the accuracy of decision-making (Codeluppi, 2020; Fuentes-Peñailillo, 2024). This transformation shows a shift towards data-driven agriculture that relies on the integration of information and communication technology throughout the production cycle.

In addition, the use of artificial intelligence (AI) and machine learning further strengthens the capacity of modern agricultural systems to predict crop yields, detect pests, and perform remote sensing-based image analysis. A study conducted by Holzinger (2021) confirms that AI-based digital transformation contributes significantly to the achievement of sustainable development goals, including food security. The integration of AI with climate and agronomy data enables the development of predictive systems that are adaptive to weather variability and crop failure risks. Thus, AI-based innovations not only increase productivity but also strengthen the resilience of food systems to global uncertainty.

On the other hand, technological innovations are also developing in the areas of food governance and supply chains through the use of blockchain to improve transparency, accountability, and distribution efficiency. Research by Kamble (2020) shows that blockchain technology can enhance traceability in agricultural supply chains and reduce the risk of food fraud. Strengthening logistics systems and mitigating distribution risks have become increasingly relevant in the context of global crises and market disruptions. This confirms that agricultural technological innovation extends beyond production aspects to strengthening the entire food system from upstream to downstream. However, existing studies predominantly examine technological applications in isolation, with limited attention to the integrated relationship between technological innovation, governance mechanisms, and food security outcomes at a systemic level. Moreover, comprehensive mapping studies that synthesise the evolution, thematic structure, and emerging research directions of agricultural technology innovation in supporting food security remain scarce. Therefore, this study addresses this gap by providing a bibliometric analysis to systematically identify research trends, thematic development, and future research opportunities in this field.

However, the acceleration of technological innovation has not been fully matched by the level of adoption among farmers, especially small farmers in developing countries. Socio-economic factors, digital literacy, access to financing, and policy support are important determinants in the successful implementation of technology (Foguesatto, 2020; Blasch, 2022). Therefore, a comprehensive mapping of developments in agricultural technology innovation research is needed to identify dominant trends, research gaps, and future development directions.

2. Literature Review

Sustainable agriculture is an important foundation for achieving global food security and mitigating climate change. Adenle (2019) emphasises that technological innovation and support from international organisations play a crucial role in increasing agricultural productivity in Africa, while also ensuring food security. The concept of integrated crop nutrient management is also an important focus, especially in tropical agro-ecosystems, to improve soil fertility in a sustainable manner (Agegnehu, 2017; Bindraban, 2015; Raimi, 2017). In addition, water-saving irrigation strategies such as the Alternate Wetting and Drying (AWD) method have proven to be economically and environmentally effective, thereby supporting sustainable agricultural practices in developing countries such as Bangladesh (Alauddin, 2020; Ayars, 2015; Fishman, 2015).

The adoption of precision technology and agricultural digitalisation has become a global trend to increase production efficiency and reduce food loss. IoT-based technology, blockchain, and smart systems provide significant opportunities for more transparent and efficient agricultural supply chain management (Benyam, 2021; Bouali, 2022; Cao, 2022; Fuentes-Peñailillo, 2024; Kamble, 2020; Nayal, 2023; Yadav, 2023). Farmers' intrinsic motivation, risk perception, and policy incentives influence the adoption rate of these technologies (Bopp, 2019; Barnes, 2019; Blasch, 2022; Curry, 2021; Kolady, 2021; Kernecker, 2020). The use of integrated farming systems such as integrated crop-livestock-forestry has also been shown to improve technical efficiency and environmental sustainability (Carrer, 2020, 2022; Cortner, 2019; Gil, 2015; Garrett, 2020).

Climate-smart agriculture has emerged as a strategic approach to balancing productivity, adaptation to climate change, and mitigation of greenhouse gas emissions. The implementation of these practices, including soil conservation, efficient water management, and the use of climate-resistant varieties, has been shown to increase food security and economic benefits for farmers (Bazzana, 2022; Branca, 2021; Kabato, 2025; Ma, 2024; Ntawuruhunga, 2023; Patle, 2020; Rao, 2016; Sapkota, 2015; Sarkar, 2020; Ward, 2018). The use of bioenergy and the utilisation of agricultural waste also support the circular economy while reducing environmental impacts (Creutzig, 2015; Somasundaram, 2020; Singh, 2017; Vaneeckhaute, 2018; Yrjälä, 2022; Yu, 2024).

In the context of technology adoption, the literature highlights the importance of smart data and smart sensors to support evidence-based decision-making in precision agriculture (Lindblom, 2017; Liniger, 2019; Soussi, 2024; Victor, 2024). Meanwhile, digital transformation in the agricultural sector also requires attention to security, privacy, and technological sustainability to support sustainable development goals (Holzinger, 2021). The adoption of sustainable agricultural technologies and practices is influenced not only by technical aspects, but also by socio-economic, cultural, and regulatory factors at the local and global levels (Liverpool-Tasie, 2020; Meemken, 2018; Serebrennikov, 2020; Sharma, 2024).

Thus, this research theoretical framework emphasises three main pillars: (1) sustainable agricultural practices and resource management, (2) the adoption of precision technology and digitalisation in agriculture, and (3) climate-smart agricultural strategies to support food security and environmental sustainability. The integration of these three pillars is expected to form a conceptual basis for analysing the impact of agricultural technologies and practices on the productivity, efficiency, and sustainability of modern agricultural systems.

3. Methods

This study uses a quantitative bibliometric approach to analyse the intellectual structure, development dynamics, and evolutionary direction of agricultural technology innovation research in supporting food security. Bibliographic data was systematically obtained from the Scopus database because it has extensive coverage of reputable international journals and provides standardised and comprehensive citation metadata. The search strategy was carried out using a combination of key words, namely ‘Sustainable Agriculture’, ‘Technology Adoption in Agriculture’, ‘Agricultural Technology Innovation’, ‘Food Security’, ‘Agricultural Research Trends’, ‘Innovation in Farming Systems’, and ‘Agricultural Development’, which were integrated using Boolean operators (AND, OR) to ensure the relevance and breadth of the search results. The inclusion criteria in this study included reputable (peer-reviewed) international journal articles, written in English, and published between 2015 and 2025. The extracted metadata included article titles, abstracts, keywords, year of publication, author affiliations, number of citations, and reference lists.

The analysis stage began with data cleaning and normalisation to eliminate document duplication and standardise terminology and keyword variations to improve the validity of the network analysis. This was followed by descriptive bibliometric analysis to identify annual publication trends, citation distribution, and thematic developments in research. Keyword co-occurrence analysis was applied to map conceptual relationships between topics and identify dominant research clusters in the scientific landscape. To examine the position and maturity level of each theme, thematic mapping analysis based on a density–centrality approach was used to classify themes into motor themes, basic themes, niche themes, and emerging/declining themes. In addition, thematic evolution analysis was conducted by dividing the research period into several time phases to identify shifts in the focus of studies from a sustainable agricultural development approach to the integration of technological innovation and data-based food systems. The entire process of bibliometric network processing and visualisation was carried out using VOSviewer and Biblioshiny software to produce structured, systematic, and replicable scientific maps.

4. Results and Discussion

4.1. Research Results

Based on the results of literature searches in relevant databases, 489 articles were identified in the initial stage. These were then screened through a process of title and abstract selection, duplication removal, and full-text review in accordance with the established inclusion and exclusion criteria. From this process, 67 articles were selected that met the criteria and were relevant to the focus of the study.

Figure 1. Cleaned Bibliometric Keyword Visualisation

The visualisation of cleaned bibliometric keywords as in figure 1 shows that the research landscape is dominated by the major themes of agriculture, agricultural, technology, precision, plant, food, learning, smart farming, and innovation, which are displayed in the largest font size as indicators of the highest frequency of occurrence. This indicates that the main direction of research focuses on technology-based agricultural transformation, particularly the integration of precision agriculture, machine learning, and digital systems in supporting food production. The presence of keywords such as IoT, sensors, monitoring, UAV, detection, prediction, imaging, and hyperspectral reinforces the finding that artificial intelligence and data analysis approaches are the main foundations in the development of modern agricultural systems. In addition, the emergence of terms such as yield, growth, soil, irrigation, and productivity indicates a strong orientation towards increasing efficiency and optimising crop yields. The global and sustainability dimensions are also evident through keywords such as food security, climate change, and sustainability, although visually they are not as dominant as the technology theme. Overall, this word map confirms that current research tends to be technology-centric with a focus on digital innovation in precision agriculture, while social, policy, and farmer adoption aspects are still relatively less prominent and have the potential to become research gaps in the future.

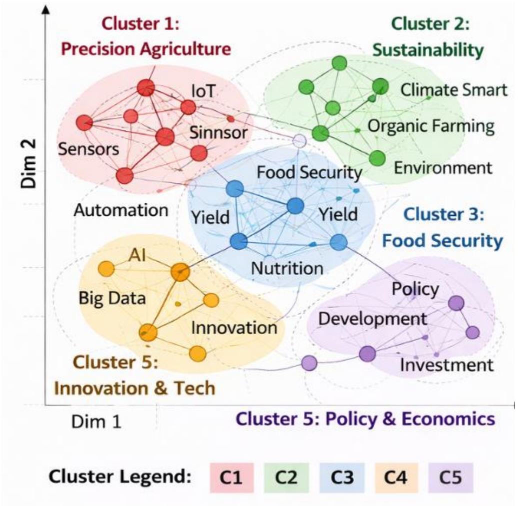

Figure 2. Cluster Map (Keyword Co-occurrence)

Figure 2 consists of a cluster map used to map the development of research on agricultural technology innovation in supporting food security. In the cluster map (keyword co-occurrence) section, keywords that frequently appear together are grouped into several thematic clusters. The first cluster focuses on Precision Agriculture, which includes IoT, sensors, and automation, indicating a strong research focus on agricultural digitalisation. The second cluster relates to Sustainability and Climate Smart Agriculture, emphasising environmental sustainability and climate change adaptation issues. The third cluster places Food Security at the core, linked to yield and nutrition, indicating that increasing food production and quality is a key objective of innovation. Other clusters relate to innovation and technology such as AI and big data, as well as policy and economic aspects such as policy, investment, and development. This cluster division shows that research is not only technology-oriented but also focuses on environmental and policy dimensions.

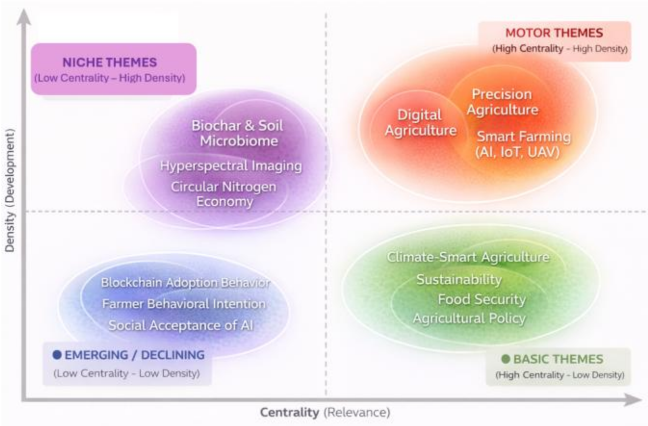

Figure 3. Thematic Map (Density–Centrality)

The thematic map shown in figure 3 based on density–centrality analysis shows the structured intellectual configuration in digital and sustainable agriculture research. The upper right quadrant identifies precision agriculture, digital agriculture, and smart farming (AI, IoT, UAV) as motor themes, characterised by a high level of internal development and strong network centrality. These themes serve as the main drivers of the research field, reflecting conceptual maturity and solid integration within the scientific network. On the other hand, climate-smart agriculture, sustainability, food security, and agricultural policy emerge as basic themes, which have high centrality but relatively lower density, indicating a fundamental and cross-thematic role despite not yet being developed specifically and deeply in this research cluster. Meanwhile, specific topics such as biochar and soil microbiome, hyperspectral imaging, and circular nitrogen economy occupy the niche themes quadrant, indicating strong internal cohesion but limited connectivity with the main themes. Social-behavioural constructs such as blockchain adoption behaviour, farmer behavioural intention, and social acceptance of AI are in the emerging/declining quadrant, indicating a research direction that is still developing and has the potential to be transformational in the future. Overall, these findings confirm the dominance of the technological paradigm in digital agriculture, supported by a foundation of sustainability and a shift in attention towards social dimensions and human-centred agriculture.

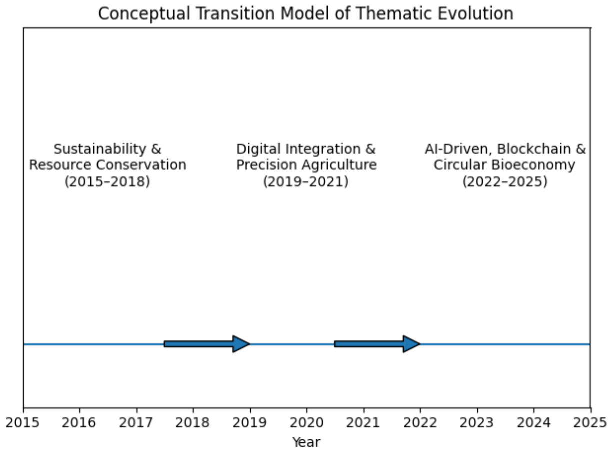

Figure 4. Thematic Evolution

Thematic evolution in figure 4 shows a progressive transformation in the landscape of agricultural and food systems research during the period 2015–2025. In the first phase (2015–2018), research focus was still dominated by issues of sustainability and resource conservation. Studies during this period emphasised sustainable agronomic practices, efficient use of water and land, and natural resource management in response to the challenges of environmental degradation and climate change. The orientation of the research was still normative and practice-based.

Entering the second phase (2019–2021), there was a shift towards the integration of digital technology in agricultural systems, marked by increased attention to digital agriculture and precision agriculture. At this stage, research began to adopt sensors, the Internet of Things (IoT), big data, and data-based monitoring systems to improve production efficiency and decision-making accuracy. This transformation signalled a shift from conventional approaches to information technology-based agricultural systems.

In the third phase (2022–2025), the thematic evolution increasingly pointed towards high-tech food systems, marked by the dominance of AI-driven agriculture, the integration of blockchain for supply chain transparency, and the development of circular bioeconomy systems. Research no longer focuses solely on increasing productivity, but also on systemic transformation that integrates artificial intelligence, digital governance, and circular economy models. This shift reflects a transition from an agronomic practice-based approach to a digitised, automated, and data-driven food ecosystem.

Overall, this thematic evolution shows that research is moving from a conservation-based sustainability paradigm towards a digital transformation and artificial intelligence paradigm. This confirms that modern agricultural systems are no longer understood solely as production activities, but as complex systems integrated with technology, data, and institutional innovation.

Figure 5. Conceptual Evolution Framework

This Conceptual Evolution Framework in figure 5 illustrates the development of agricultural technology innovation research for food security in four main phases. In the initial phase (2015–2018), research focused on the foundations of sustainability, such as agricultural conservation, irrigation efficiency, and soil fertility management. Entering the 2018–2020 phase, attention shifted towards sustainable intensification and farmer adoption studies, where social, economic, and behavioural aspects began to play an important role in the successful implementation of technology. Furthermore, the 2020–2022 period saw an acceleration of digitalisation through the integration of IoT, blockchain, smart farming, and data-based systems that expanded the scope of innovation from the field level to the supply chain system. In the latest phase (2023–2025 and beyond), research is evolving towards the integration of artificial intelligence (AI), remote sensing, and Industry 5.0 concepts, leading to integrated, digital, and climate-resilient food systems.

Conceptually, this evolution represents a shift from physical technologies to data-driven and artificial intelligence-based solutions, from a focus on land productivity to food system sustainability, and from standalone innovations to cross-sector integration that supports long-term food security.

Table 1. Mapping of Agricultural Technology Innovation Research for Food Security

Innovation Group	Technology Focus / Approach	Contribution to Food Security	References
Blockchain & Digital Supply Chain	Blockchain traceability, sustainable agri-food supply chain, risk mitigation	Supply chain transparency, reduction of food fraud, increased market confidence, food distribution stability	(Y. Cao, 2022; Kamble, 2020; Mangla, 2021; Nayal, 2023; Saurabh, 2021; Yadav, 2023)
IoT & Smart Farming Systems	IoT architecture, sensor networks, cloud-based farming, smart monitoring	Production efficiency, reduction of yield losses, optimisation of agricultural inputs	(Bouali, 2022; Codeluppi, 2020; Fuentes-Peñailillo, 2024; Namani, 2020; Sharma, 2024; Soussi, 2024)
Artificial Intelligence & Machine Learning	AI crop monitoring, weed detection, remote sensing analytics	Increased productivity and precision of land management	(Holzinger, 2021; Pugliese, 2021; Vasileiou, 2024; Victor, 2024)
Precision Agriculture	Decision support systems, sensor-based farming, efficiency analysis	Input optimisation, increased crop yields, production cost efficiency	(Barnes, 2019; Carrer, 2022; Kernecker, 2020; Kolady, 2021; Lindblom, 2017)
Climate-Smart Agriculture (CSA)	Climate change adaptation, emissions	Long-term food security and production stability	(Bazzana, 2022; Branca, 2021; Kabato, 2025; Ma, 2024; Ntawuruhunga, 2023)

Innovation Group	Technology Focus / Approach	Contribution to Food Security	References
	mitigation, policy integration		
Conservation & Low-Carbon Farming	No-till, mulching, carbon footprint reduction	Reduced land degradation, energy efficiency, production sustainability	(Fuentes-Llanillo, 2021; Somasundaram, 2020; Tambo, 2018; Ward, 2018)
Water & Irrigation Innovation	Drip irrigation, groundwater efficiency, climate-smart water technologies	Water efficiency, production stability in drought-prone areas	(Alauddin, 2020; Ayars, 2015; Fishman, 2015; Patle, 2020; Suwaileh, 2020)
Soil & Nutrient Management	Soil fertility, nutrient recovery, biofertilizer, nitrogen cycle	Increased soil fertility and long-term productivity	(Agegnehu & Amede, 2017; Bindraban, 2015; Raimi, 2017)
Bio-based & Circular Agriculture	Biochar, nutrient recycling, waste valorization	Resource efficiency and reduction of food system waste	(R. Cao, 2023; Mehta, 2015; Vaneeckhaute, 2018; Yrjälä, 2022; Yu, 2024)
Agroecology & Sustainable Intensification	Agroecological transition, yield gap reduction	Increased sustainable production to meet food needs	(Anderson, 2016; Kuyah, 2021; Meemken, 2018; Sarkar, 2020)
Adoption & Behavioral Studies	Behavioral intention, socio-economic drivers, farmer perception	Accelerated diffusion of innovation and increased technology adoption	(Blasch, 2022; Bopp, 2019; Curry, 2021; Foguesatto, 2020; Serebrennikov, 2020; Zeweld, 2017)
Policy, Governance & Institutional Support	Institutional framework, rural credit, governance systems	Strengthened food systems through policy support	(Adenle, 2019; Carrer, 2020; Dorairaj, 2023; Liniger, 2019; Rao, 2016)
Renewable Energy & Bioenergy	Bioenergy, decentralized biomass power, renewable integration	Diversification of agricultural energy and production system resilience	(Bouali, 2022; Creutzig, 2015; Singh, 2017)
Integrated Crop-Livestock & Diversification	Integrated systems, sustainable intensification	Production diversification and farmer income stability	(Cortner, 2019; Garrett, 2020; Gil, 2015; Mueller, 2015)
Food Loss & Value Chain Efficiency	Food loss reduction, logistics risk mitigation	Distribution stability and increased food availability	(Benyam, 2021; Liverpool-Tasie, 2020; Sharma, 2024; Yadav et al., 2022)

Based on Table 1, the direction of research development tends to focus on integrating modern technology with conventional agricultural production systems in order to increase productivity, efficiency, and sustainability. The majority of research emphasises the application of digital-based technologies such as the Internet of Things (IoT), smart sensor systems, precision agriculture, and the use of artificial intelligence to monitor soil conditions, weather, and plant nutritional needs in real time. This indicates a paradigm shift from traditional approaches to data-driven agriculture, which can minimise the risk of crop failure and improve decision-making accuracy.

In addition, innovation is not only oriented towards production aspects but also includes the efficient use of resources such as water and fertilisers through smart irrigation technology and the development of superior varieties that are resistant to climate change. Research related to biotechnology and genetic engineering also shows a significant contribution in creating crops that are more adaptive to climate change and pest attacks. Thus, agricultural technology innovation is positioned as a strategic solution in responding to the food crisis caused by population growth and global climate change.

In terms of implementation, research mapping indicates that collaboration between the government, academia, and the private sector is a key factor in accelerating technology adoption. However, there are still challenges in the form of limited digital literacy among farmers, access to financing, and infrastructure gaps in rural areas. Therefore, a comprehensive policy approach is needed, not only to encourage technological innovation, but also to ensure knowledge transfer and equitable accessibility so that these innovations have a real impact on improving national food security in a sustainable manner.

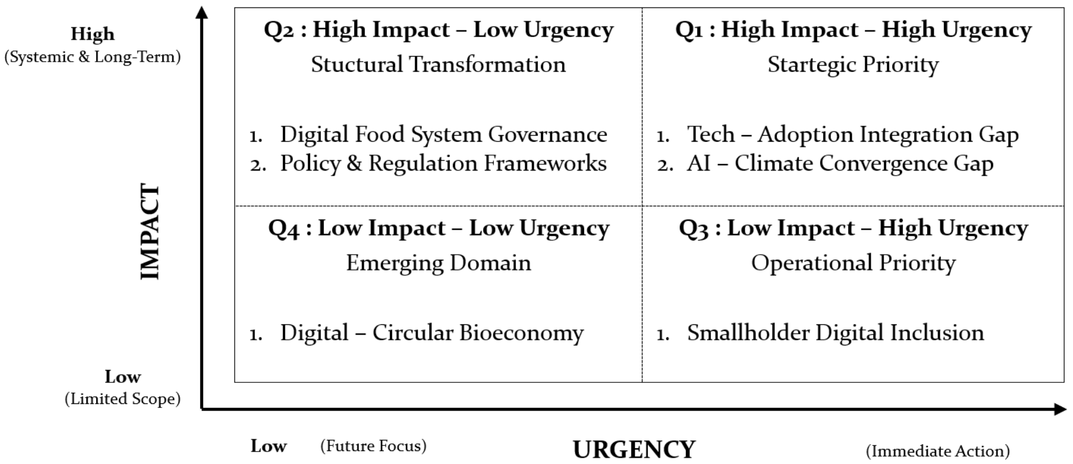

Figure 6. Research Gap Matrix

Based on Figure 6, research gaps with high impact and high urgency occupy the top strategic priority, namely the integration between technology development and adoption, and the convergence of artificial intelligence with climate change adaptation. These two issues have systemic implications for food security and require immediate attention because the acceleration of digital innovation has not been fully matched by social, institutional, and regulatory readiness. In addition, the increasing risks of climate change demand the integration of AI-based predictive systems into agricultural practices in a more operational manner. At the next level, digital food system governance and policy framework strengthening fall into the high impact but lower urgency category, as they are structural in nature and require a consistent, long-term reform process.

Meanwhile, digital inclusion for smallholder farmers falls into the high urgency but lower systemic impact category, although it remains important to prevent a widening of the technology gap in the food system. The integration of a digital-based circular economy is still a developing field with relatively lower impact and urgency, but it has strategic potential in supporting long-term sustainability. Overall, this matrix shows that future research should prioritise technology integration and climate adaptation as the main focus, accompanied by strengthening governance and ensuring social inclusion to build a resilient and sustainable food system.

Table 2. Citation Structure Matrix

Dimensions of Analysis	Themes	Citation Direction	Interdisciplinary Pattern	Level of Influence	Implications for Research Development
Foundational Core	Precision Agriculture	Cited by AI, sustainability, climate adaptation	Engineering → Sustainability Science → Environmental Policy	Very High	Forming the methodological foundation for digital agricultural transformation
Foundational Core	Climate Smart Agriculture	Cited by food security and public policy studies	Environmental Science → Food Security → Policy Studies	High	Establishing a framework for production integration and climate resilience
Emerging High Growth	Artificial Intelligence in Agriculture	Citing precision agriculture and climate datasets	Computer Science ↔ Agronomy ↔ Climate Science	Very High	Promoting data-driven predictive systems and automated decision-making
Emerging High Growth	Blockchain in Food Supply Chain	Citing supply chain management and food safety	Information Systems ↔ Logistics ↔ Food Security	High	Strengthening food system governance and accountability
Governance Integration	Digital Food Governance	Citing AI, blockchain, and sustainability frameworks	Policy Studies ↔ Data Science ↔ Sustainability	Medium–High	Highlighting the need for policy integration and digital innovation
Sustainability Transition	Circular Bioeconomy & Agri-Tech	Citing sustainability and industrial ecology	Sustainability Science ↔ Agricultural Innovation ↔ Industrial Ecology	Medium	Supporting low-carbon food systems and resource efficiency

Table 2 shows that research on agricultural technology innovation for food security forms a pattern of interconnected conceptual clusters across disciplines. Foundational core themes, such as precision agriculture and climate-smart agriculture, are the most cited publications and serve as methodological and conceptual foundations. Precision agriculture bridges the fields of engineering and sustainability science, while climate-smart agriculture connects environmental science with food security studies and public policy. These two themes have a high systemic influence and form the basis for the development of more complex agricultural technology research.

On the other hand, rapidly developing themes, such as artificial intelligence in agriculture and blockchain for the food supply chain, show a significant acceleration in citations. Artificial intelligence connects computer science, climatology, and agronomy, while blockchain connects information systems, logistics, and food security. The themes of governance integration and circular bioeconomy show interdisciplinary citation patterns that emphasise digital governance and long-term sustainability. Overall, these citation patterns confirm that agricultural technology innovation research does not only focus on technical aspects but also involves cross-disciplinary integration to build a resilient, efficient, and sustainable food system.

4.2. Discussion

The results of the bibliometric analysis show that the intellectual structure of agricultural technology innovation research for food security is dominated by technological paradigms, particularly precision agriculture, artificial intelligence (AI), the Internet of Things (IoT), and smart farming. This dominance reflects the consolidation of research directions that place technical efficiency, input optimisation, and data-driven decision-making as the main focus of scientific development. Precision agriculture, in this case, is no longer positioned merely as an operational efficiency approach, but as a methodological foundation that integrates productivity and environmental sustainability (Finger, 2019; Lindblom, 2017). Various empirical studies show that the adoption of precision technology contributes to increased technical efficiency and agricultural productivity (Carrer, 2022; Kolady, 2021). However, the growing literature tends to position technology as an inherent solution without being balanced by critical analysis of distributional implications, access gaps, and adoption capacity among farmers. Thus, there is a tendency towards technological optimism that does not fully consider the structural dimensions of the agrarian system.

The integration of artificial intelligence into agricultural systems further reinforces this orientation. The use of machine learning for weed detection, crop growth monitoring, and remote sensing-based image analysis demonstrates the increasing methodological complexity and predictive capabilities of modern agricultural systems (Holzinger, 2021; Vasileiou, 2024; Victor, 2024). This transformation indicates a shift from merely increasing efficiency to algorithm-based decision-making automation. However, this acceleration of digitalisation also requires adequate infrastructure, digital literacy, and data governance. The existing literature emphasises technical performance aspects rather than data ethics, information ownership, and the potential for digital exclusion, even though these aspects have significant implications for the inclusiveness of food systems.

In the context of sustainability, climate-smart agriculture (CSA) continues to function as a normative framework that integrates the goals of increasing productivity, adapting to climate change, and mitigating emissions simultaneously (Branca, 2021; Bazzana, 2022; Ma, 2024). Conceptually, CSA expands the orientation of research from short-term yield increases to long-term food system stability. However, based on thematic mapping, CSA tends to be positioned in the basic themes category with a high level of centrality but a relatively lower density of development compared to digital themes. This condition indicates an imbalance between the acceleration of digital technology-based innovation and the deepening of substantive ecological transformation.

In terms of governance and supply chains, the application of blockchain has contributed to increased transparency, traceability, and mitigation of food distribution risks (Kamble, 2020; Cao, 2022; Yadav, 2023). This innovation expands the scope of transformation from the production level to the food system as a whole. However, most studies focus on the context of formal market systems and modern supply chains, so further study is needed to generalise the benefits to traditional food systems or areas with limited infrastructure. Therefore, contextual evaluation is needed to ensure that supply chain digitalisation does not widen structural gaps in food distribution.

Furthermore, analysis of adoption clusters and farmer behaviour shows that social and institutional factors have not yet taken centre stage in mainstream research, even though empirically these factors are crucial to the successful implementation of innovations. Studies on perceptions, motivations, and intentions to adopt technology confirm that farmers' decisions are influenced by social, economic, and psychological variables, not solely by rational-economic considerations (Barnes, 2019; Foguesatto, 2020; Blasch, 2022). Thus, the gap between technological development and farmers' socio-economic readiness is a strategic issue that requires more comprehensive attention, especially in the context of developing countries.

Policy and institutional dimensions also play a significant role in accelerating the diffusion of innovation. Rural credit support, adaptive regulatory frameworks, and cross-sector coordination have been shown to influence the level of agricultural technology adoption (Adenle, 2019; Carrer, 2020; Dorairaj, 2023). However, policy literature still tends to be responsive to technological developments rather than proactive in designing a governance architecture capable of directing innovation in an inclusive and equitable manner. Without integrated policy support, digital transformation has the potential to create a dual food system between groups that have access to technology and those that are structurally disadvantaged.

Overall, the findings of this study indicate that agricultural technology innovation is evolving towards increasingly integrated data-driven and artificial intelligence-based food systems. Precision agriculture and climate-smart agriculture serve as the conceptual foundation, while AI and blockchain are the main drivers of contemporary research growth. However, the dominance of the technological paradigm indicates the need for a balance between technical progress, social readiness, institutional reform, and ecological sustainability. Digital transformation will only contribute optimally to food security if it is designed within an adaptive, inclusive, and long-term sustainability-oriented governance framework.

5. Conclusion

Based on bibliometric analysis, research on agricultural technology innovation for food security shows progressive development and increasing cross-disciplinary integration. Precision agriculture and climate-smart agriculture serve as the conceptual foundation supporting the transformation of digital agriculture. Recent developments show the dominance of artificial intelligence, IoT, blockchain, and data-based systems as the main drivers of production efficiency, supply chain transparency, and increased resilience to climate change.

Research evolution is moving from a resource conservation-based approach to a digitised food ecosystem that integrates artificial intelligence, digital governance, and the circular economy. However, the acceleration of technological innovation has not been fully matched by social, institutional, and policy readiness. High-priority research gaps include the integration of technology development and farmer adoption, the convergence of AI with climate change adaptation, and the strengthening of inclusive digital food system governance.

Therefore, future research directions need to emphasise the systemic integration of technology and sustainability, strengthen collaboration between academia, government, and the private sector, and ensure the inclusion of smallholder farmers in the digital transformation. A comprehensive and evidence-based approach will be key to building a resilient, efficient, and sustainable food system in the face of global challenges.

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