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ARTICLE

How Does the Adoption of Information and Communication Technology Improve Farmer Welfare? A Systematic Review and Bibliometric Analysis

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ABSTRACT

The adoption of Information and Communication Technology has become a crucial driver of agricultural transformation, helping farmers enhance their skills, decision-making, and access to information. This study examines whether and how the adoption of Information and Communication Technology improves farmer welfare. A systematic review following the PRISMA 2020 protocol analyzed 19 peer-reviewed articles and used bibliometric analysis in Biblioshiny (RStudio) to identify global publication trends and thematic clusters. Publications on this topic have increased significantly after 2020, reflecting rising academic, commercial, and policy interest in digital agriculture. The review demonstrates that Information and Communication Technology adoption enhances farmer welfare through five pathways: improved access to information, faster adoption of innovations, increased productivity and efficiency, expanded market and income opportunities, and strengthened social and gender inclusion. These find-

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ings support the hypothesis that digital technology adoption positively affects farmer welfare, particularly when accompanied by adequate infrastructure, institutional services, financing mechanisms, and local knowledge systems. The study contributes by: (1) integrating bibliometric and thematic evidence to provide a multidisciplinary understanding of welfare outcomes; (2) highlighting an overlooked link between digital adoption, social capital, and governance structures; and (3) developing an integrated framework that maps determinants, adoption processes, and welfare effects. These insights are valuable for global stakeholders, as strengthening rural digital infrastructure and literacy can unlock substantial economic gains by boosting productivity, reducing transaction costs, and improving market efficiency. Future research should quantify financial returns from Information and Communication Technology adoption, explore inclusive digital business models, and examine long-term environmental and socio-economic impacts.

Keywords: Information and Communication Technology; Digital Agriculture; Innovation Adoption; Farmer Welfare; Digital Literacy

1. Introduction

Agricultural transformation increasingly depends on integrating digital technologies that enhance productivity, reduce uncertainty, strengthen decision-making, and improve farmer welfare [1–5]. Despite their central role in food systems, most farmers—particularly in developing countries—operate on small landholdings and continue to experience persistent yield gaps and low-income levels, which constrain their production capacity and economic resilience [6–8]. In addition, farmers remain highly exposed to climatic variability, environmental risks, and market uncertainties, further increasing their vulnerability and livelihood insecurity [9–13]. These structural challenges underscore the need for economically viable technological solutions that support measurable gains in productivity and profitability [3–5]. These developments are also part of broader social and digital transformations occurring in rural agricultural communities [14].

Information and communication technology encompasses a broad set of tools, including mobile phones, computers, digital platforms, sensors, databases, radio systems, and satellite-based services [15–17]. Beyond information dissemination, these technologies increasingly facilitate real-time decision-making, market intelligence, financial inclusion, logistics coordination, and risk management [18–20]. Recent developments, such as AI-assisted advisory services, Internet of Things (IoT) monitoring systems, and digitally enabled governance, are gradually influencing agricultural transformation by improving access to information and reducing transaction inefficiencies [17,20]. These shifts also reflect broader patterns of innovation diffusion, in which the uptake of new technologies spreads across communities based on perceived benefits, compatibility, and ease of use [21]. Evidence from Africa and Asia indicates that digital tools can improve farm productivity and support farmers' readiness, adoption, and participation in agricultural markets by reducing information asymmetry [22–25]. Complementary evidence from Africa and Europe further shows that ICT use contributes to collective action, improved risk management, and strengthened rural livelihoods across diverse institutional contexts [26,27].

However, the literature on ICT adoption remains fragmented across regions and disciplines, with inconsistent findings on the determinants that shape adoption and the mechanisms through which ICT adoption influences welfare outcomes [18,22,24,27]. While many studies emphasize digital literacy, infrastructure, institutional support, and socio-economic characteristics, their interrelationships and cumulative effects require deeper synthesis [22–26]. Furthermore, emerging issues such as digital inequality, data governance, platform dependency, and technology readiness remain underexplored in existing reviews [17,22,27].

Insights from sustainability-oriented agricultural systems highlight the global demand for efficient, technology-enabled solutions that balance environmental and economic objectives [7,8,14]. These perspectives

reinforce the importance of understanding how ICT adoption contributes not only to improved decision-making and productivity but also to long-term welfare and adaptive capacity within farming communities [14,28].

Given these gaps, this study provides a comprehensive synthesis of the scholarly landscape on digital agriculture by mapping global research trends on ICT adoption and identifying the key determinants that shape its utilization across diverse socio-economic and institutional contexts [17,22–25]. Furthermore, the study examines the pathways through which ICT contributes to improvements in farmer welfare, including livelihood resilience, collective action, and farmer independence, as documented in recent empirical studies [26–28]. To consolidate the fragmented evidence base, this review combines a systematic literature review with bibliometric analysis, enabling the development of an interdisciplinary framework that links determinants, adoption mechanisms, welfare outcomes, and policy implications [17,21,22]. Building on this foundation, the study posits that the adoption of Information and Communication Technology is shaped by the availability of adequate infrastructure, institutional support, and economic incentives across diverse agricultural contexts [17,22–25]. When these enabling conditions are in place, ICT adoption is more likely to translate into measurable improvements in farmer welfare, including productivity gains, livelihood resilience, and farmer independence [26–28]. This hypothesis is particularly relevant within the environmental–economic nexus, as digital agriculture offers significant opportunities to enhance profitability, reduce production risks, and strengthen long-term sustainability in global food systems [1–5,14,17].

2. Method

This study employed a systematic literature review (SLR) combined with bibliometric analysis to synthesize evidence on the determinants of Information and Communication Technology adoption and its implications for farmer welfare. The review followed the PRISMA 2020 guidelines [29], which include four stages: identification, screening, eligibility assessment, and inclusion. The search strategy applied predefined keywords related to "ICT", "digital agriculture", "innovation adoption", and "farmer welfare" within the Scopus database. Only peer-reviewed journal articles were included to ensure academic rigor, as shown in **Figure 1**.

2.1. Coding and Thematic Synthesis

The qualitative synthesis followed a structured, multi-stage coding procedure. First, an initial set of analytical categories was developed based on the review objectives and insights from the bibliometric keyword co-occurrence clusters. These categories guided the first-cycle open coding of all included articles. Next, axial coding was applied to connect determinants, adoption mechanisms, and welfare outcomes. The thematic synthesis then integrated these coded patterns into higher-order themes that aligned with the conceptual framework.

2.2. Reliability and Validity Procedures

To ensure methodological transparency and consistency, all coding was conducted manually in accordance with a predefined protocol. An audit trail was maintained to document analytical decisions throughout the process. In addition, the emerging thematic structure was reviewed by a peer colleague through a peer-debriefing procedure to enhance interpretive clarity and coherence. Cross-checking thematic patterns against bibliometric clusters further strengthened analytic validity.

2.3. Bibliometric Integration

The bibliometric analysis, conducted with Biblioshiny (RStudio), examined publication trends, keyword co-occurrence networks, thematic clusters, and influential authors. These outputs informed the qualitative synthesis by shaping the initial analytical categories and supporting the validation of emerging themes. For example, clusters such as "digital literacy," "mobile phones," and "farm productivity" guided the construction of thematic dimensions in the SLR.

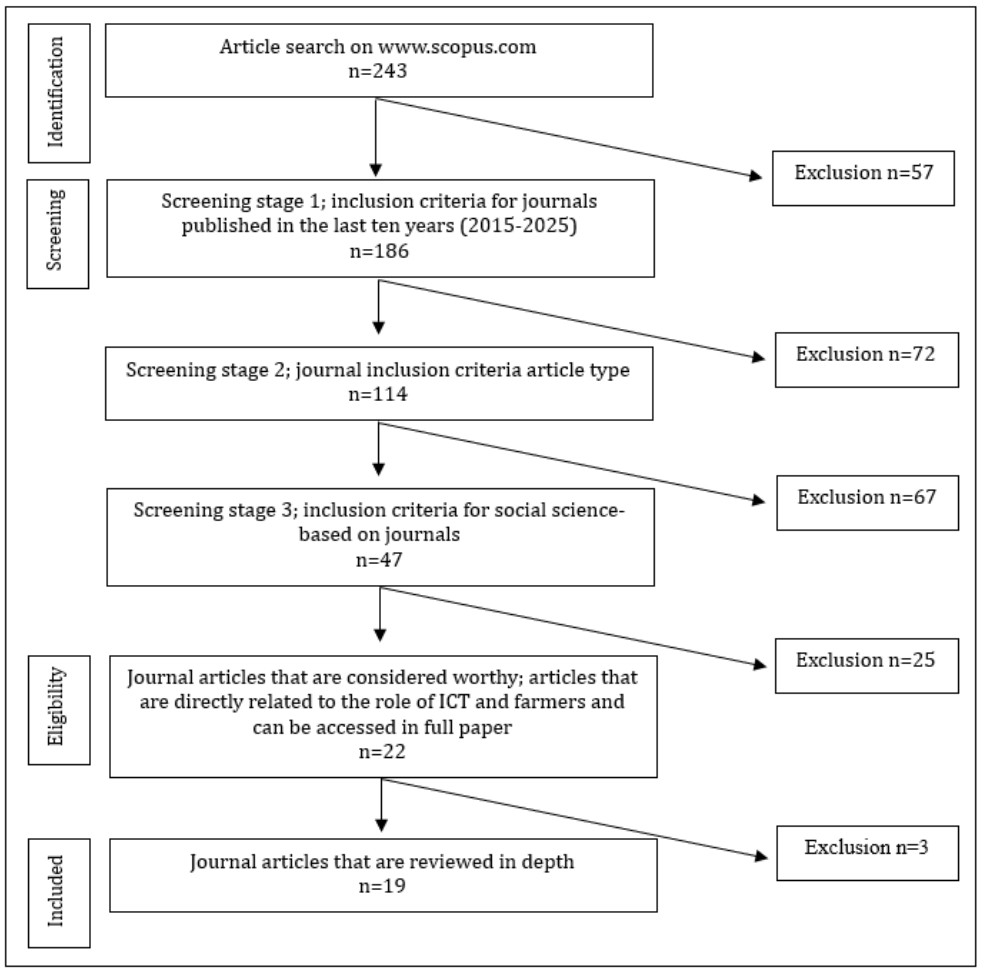


Figure 1. PRISMA 2020 flowchart.

2.4. Limitations

A key methodological limitation is the reliance on the Scopus database alone, which may exclude relevant studies indexed in Web of Science, Dimensions, or regional repositories. Nevertheless, Scopus was selected for its comprehensive coverage of agricultural and digital-technology literature, providing a broad representation of global scholarship.

3. Results

3.1. Summary of Included Studies

A total of 19 empirical studies met the inclusion criteria. The studies cover diverse geographical regions, including Africa, Asia, and Europe, and employ methodological approaches ranging from household surveys and randomized trials to mixed-methods and participatory research designs. ICT types documented across studies include mobile phones, radio, digital platforms, internet services, social media, decision-support systems, and IoT-based devices.

Table 1 presents a consolidated overview of author(s), publication year, country, methodological design, ICT type, and key findings. The included studies reveal notable geographical variation: African and South Asian research commonly emphasizes infrastructure and affordability constraints; Southeast Asian studies highlight institutional capacity, digital literacy, and governance; while European research centers on policy frameworks and digital ecosystem maturity.

Table 1. Summary of the 19 reviewed studies.

No	Author (s)/Year	Country	Method	ICT Type	Key Finding
1	Al-Ammary and Ghanem (2024) [22]	Bahrain	Survey	Digital infrastructure, literacy apps	Productivity, cost efficiency
2	Karubanga et al. (2024) [30]	Uganda	Mixed-methods/ extension study	Extension video	Social empowerment, participation
3	Touri (2024) [31]	Global (theoretical)	Conceptual analysis	ICT in development	Access to information, risk of digital exclusion
4	Shaleh et al. (2024) [32]	Indonesia	Survey (potato farmers)	ICT for pesticides, farm apps	Pesticide reduction, environmental sustainability
5	Ma et al. (2023) [33]	China	Household survey	ICT, mobile phones, credit apps	Income, credit access, women's empowerment
6	Kabirigi et al. (2023) [23]	Rwanda	Survey	Mobile phones	Productivity, efficiency, and market information
7	Pělucha et al. (2023) [27]	Czech Republic	Micro-study/ qualitative	Digitalisation, policy, ICT tools	Digital exclusion, inequality
8	Akter and Tan (2023) [34]	Bangladesh	Case study	Mobile apps	Market information, bargaining power
9	Midamba et al. (2023) [35]	Uganda	Survey	Sustainable agriculture platforms (SAPs)	Productivity, farm efficiency
10	Wu et al. (2022) [36]	China	Mixed-method	Digital governance tools	Environmental sustainability, resilience
11	Adeniyi et al. (2022) [37]	Nigeria	Survey	Crisis-adaptation (Covid-19 ICT)	Adaptation strategies, food sustainability
12	Reissig et al. (2022) [38]	Switzerland	Conceptual analysis	E-government services	Barrier identification, administrative burden
13	Cieslik et al. (2021) [26]	Ethiopia	Case study	Collective ICT tools (blight management)	Food security, collective coordination
14	Kumar et al. (2020) [39]	Bangladesh	Survey	Weather/climate information apps	Climate adaptation, access to information
15	Mwalupaso et al. (2019) [25]	South Africa	Survey	Mobile phones	Increased income, market access
16	Simelane et al. (2019) [40]	South Africa	Field application	Mobile extension apps	Efficiency, productivity, food security
17	Borrero (2019) [41]	Spain	Case study	Blockchain traceability	Value chain transparency and improved income
18	Munthali et al. (2018) [42]	Ghana	Comparative study	ICT platforms, digital extension	Social empowerment, access to information
19	Maredia et al. (2018) [43]	Burkina Faso	Field experiment	Animated videos	Innovation adoption, knowledge gains

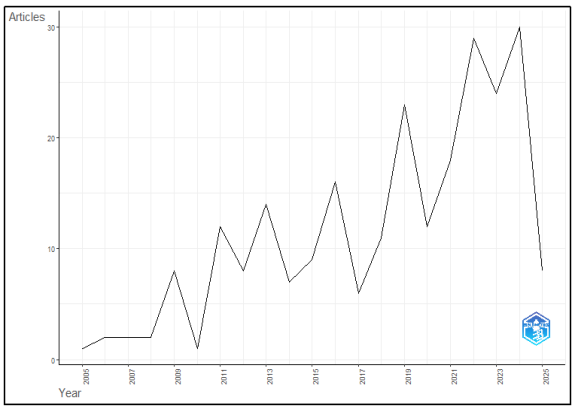
Source: processed by the author (2025).

3.2. Bibliometric Results

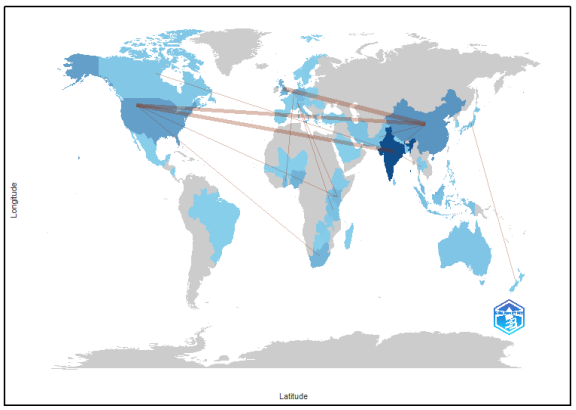
Bibliometric analysis using Biblioshiny (RStudio) identified a sharp increase in publications from 2020 onward, indicating intensified global attention to digital agriculture. The bibliometric mapping also highlights global collaboration networks, institutional affiliations, and thematic trends that structure the evolution of ICT-related agricultural research. **Figure 2** consists of four panels illustrating different bibliometric dimensions: (a) annual publication growth, (b) cross-country collaboration networks, (c) institutional affiliations, and (d) trending research topics.

The visual patterns in **Figure 2** show that research output accelerated sharply after 2020, with strong collaborations emerging between Asia, Europe, and Africa. Highly productive institutions, such as ICAR, Tamil Nadu Agricultural University, and the University of Nigeria, indicate regional concentrations of expertise. Trending-

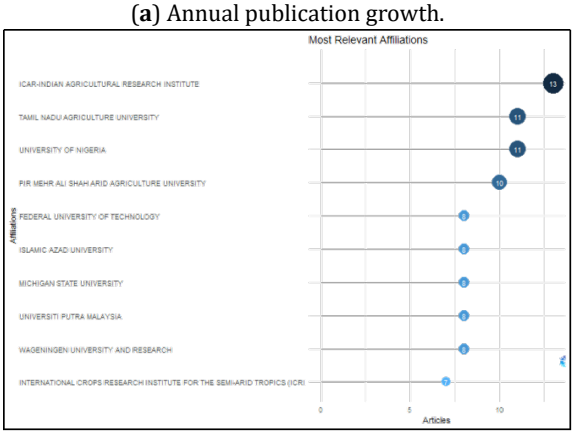
topic mapping further demonstrates a shift from basic ICT concepts toward more advanced themes, including precision agriculture, digital platforms, and decision-support technologies.



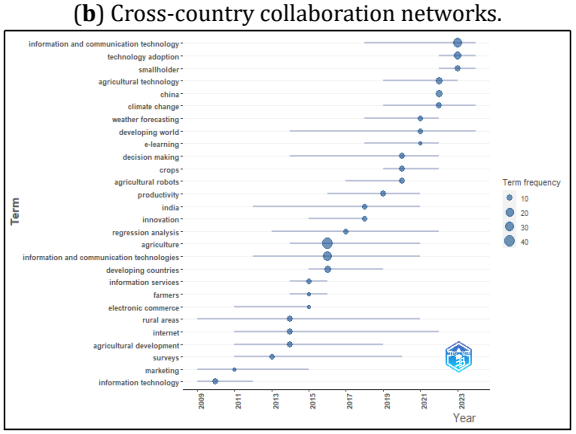
(**a**) Annual publication growth.



(**b**) Cross-country collaboration networks.



(**c**) Institutional affiliations.



(**d**) Trending research topics.

Figure 2. Bibliometric mapping of ICT research in agriculture (2005–2025).

Keyword co-occurrence mapping revealed three dominant clusters:

1. Digital access and infrastructure ("mobile phones", "internet access", "connectivity", "rural ICT");
2. Technology-enabled farming and innovation ("precision agriculture", "IoT", "digital platforms", "information services");
3. Socio-economic and institutional perspectives ("farmer welfare", "adoption", "extension services", "social capital").

These clusters directly informed the initial coding categories in the thematic synthesis. The overlap between bibliometric and qualitative findings strengthens the validity of the results, particularly the consistency of determinants such as digital literacy, institutional support, and affordability.

3.3. Thematic Determinants of ICT Adoption

Seven thematic determinants were identified across the 19 studies:

1. Socio-demographic factors. Age, education, gender, farming experience, and household size influence the likelihood of adoption. Younger, more educated farmers adopt ICT more readily, a pattern consistent across Africa and Asia.
2. Digital access and rural ICT infrastructure. The availability of mobile networks, the affordability of devices/data, and access to electricity are critical enablers. Infrastructure gaps remain the most binding constraint in Africa and South Asia.
3. Digital literacy and farmer capability. Limited digital skills reduce farmers' confidence and perceived usefulness of ICT tools. Studies in India, Indonesia,

Rwanda, and Nigeria consistently highlight the importance of training.

4. Institutional support (extension, cooperatives, NGOs). Institutions mediate information flows, assist with onboarding to ICT apps, and confer legitimacy. Strong extension systems (Indonesia, Ethiopia) significantly accelerate adoption.
5. Governance, policies, and enabling ecosystem. Policy incentives, subsidies, data governance, and farmer-protection mechanisms influence trust and uptake. European studies emphasize regulatory clarity; developing regions stress program continuity.
6. Economic and market incentives. Perceived profitability and clear economic benefit drive adoption. Farmers adopt ICT more readily when outcomes relate to price discovery, reduced risk, or improved bargaining power.
7. Social capital and network structures. Peer influence, farmer group dynamics, and trust relationships shape adoption decisions. ICT spreads faster within groups with intense bonding and bridging social capital.

These determinants are not isolated; instead, they interact dynamically. For example, digital literacy moderates the effectiveness of institutional support, while infrastructure conditions shape economic incentives.

3.4. Welfare Outcomes and ICT Adoption Pathways

Five major pathways were identified through which ICT contributes to welfare:

1. Improved access to information. ICT tools, such as mobile phones, advisory platforms, and digital databases, enable farmers to access timely information on weather, pests, prices, agronomic practices, and input availability. This reduces uncertainty, strengthens decision-making, and enhances planning capacity.
2. Faster adoption of innovations. ICT accelerates the diffusion of new technologies by facilitating exposure to training materials, demonstration videos, and peer learning. Digital extension tools and ICT-enabled farmer networks reduce information lags, allowing innovations to spread more quickly across communities.
3. Productivity and farm efficiency. Real-time agronomic information and decision-support systems improve crop management, reduce losses, and enhance input-use efficiency. Studies show measurable gains in yield, resource efficiency, and environmental performance.
4. Market access and income diversification. Mobile phones and digital platforms connect farmers with buyers, improve price transparency, reduce transaction costs, and create opportunities for value addition. These mechanisms directly contribute to higher, more stable farm incomes.
5. Social and gender empowerment. ICT strengthens communication, expands women's access to training, improves group coordination, and enhances participation in decision-making processes. Digital tools help reduce social barriers and support more inclusive farmer organisations.

Across the reviewed studies, these welfare outcomes show substantial regional variation. In Africa, gains stem largely from improved price information; in Asia, strong extension systems amplify productivity effects; and in Europe, ecosystem maturity and digital governance shape welfare outcomes. Collectively, these patterns demonstrate that ICT-driven welfare improvements are highly context-dependent and shaped by technology characteristics, institutional arrangements, and enabling environments.

4. Discussion

4.1. Interpreting How ICT Shapes Behaviour and Welfare

The findings of this review demonstrate that the dynamic interaction between infrastructure availability, institutional capacity, farmer capability, and the perceived economic benefits of innovation shapes the adoption of Information and Communication Technology (ICT) in agriculture. These dynamics reflect how farmers evaluate new technologies under uncertainty, aligning with the Diffusion of Innovations framework, which empha-

sizes relative advantage, compatibility, complexity, and trialability as key determinants guiding adoption decisions[21]. When ICT increases the availability, accuracy, and timeliness of agricultural information, farmers develop stronger perceptions of usefulness, thereby strengthening their behavioural intentions to adopt ICT.

At the same time, the review shows that ICT adoption is mediated through group structures and community interactions; patterns that are strongly aligned with the assumptions of Social Capital Theory[28]. Trust relationships, group cohesion, and leadership structures strongly influence the circulation of information and collective learning. Farmer organisations and community networks, therefore, act as intermediaries that amplify the impact of ICT, enabling farmers to convert information into coordinated action. These insights reaffirm that ICT should not be viewed solely as a technical artefact, but rather as a socio-technical instrument shaped by institutional and cultural contexts.

Beyond individual decision-making, the interaction between ICT and institutional environments further explains why adoption outcomes vary across contexts. Where extension systems, cooperatives, and local governance structures are actively engaged, ICT adoption tends to move beyond information access toward sustained behavioural change and welfare improvement. Conversely, in settings with weak institutions or fragmented support systems, digital tools are often underutilised or adopted only superficially. This finding suggests that the effectiveness of ICT adoption depends not only on technological availability but also on enabling organisational arrangements that support learning, trust-building, and collective problem-solving. As a result, ICT adoption should be understood as an embedded process that unfolds within broader social, institutional, and economic systems rather than as a purely individual or technology-driven choice.

4.2. Regional and Technological Variation in ICT Outcomes

Cross-regional analysis reveals that ICT adoption is highly context-dependent. In African countries, the effectiveness of digital tools is strongly influenced by mobile-phone penetration, affordability constraints, and variable connectivity. Asian studies, in contrast, highlight the strong complementarity between ICT and agricultural extension services, demonstrating that digitally enabled advisory systems can substantially strengthen learning and decision-making. European studies emphasise the significance of supportive regulatory environments and digital governance, where institutional clarity reduces transaction costs and facilitates more advanced forms of adoption.

Technology type also plays a significant role in shaping outcomes. Mobile phones support communication, market linkage, and price discovery; digital platforms and mobile applications enhance productivity by offering decision-support and advisory content; radio and SMS-based systems remain essential in low-literacy environments, while IoT-based technologies provide high-precision benefits but require significant infrastructure and financial investment. These variations indicate that ICT adoption is most effective when technology characteristics align with local socio-economic conditions and institutional arrangements.

These regional and technological variations suggest that ICT adoption cannot be governed through uniform policy or technological prescriptions. In contexts where basic connectivity and affordability remain limiting factors, incremental, low-cost digital solutions may yield greater welfare impacts than sophisticated platforms. Conversely, in regions with more mature digital ecosystems, the integration of advanced applications, data-driven services, and regulatory frameworks becomes increasingly relevant. This differentiation underscores the importance of tailoring digital agriculture strategies to local institutional capacity, market structures, and technological readiness, thereby avoiding mismatches between technology design and farmers' actual conditions.

4.3. Extending Insights beyond Prior Review Literature

Compared with earlier reviews published between 2021 and 2023, this study makes several conceptual advancements. The integration of systematic literature review with bibliometric analysis enables a more rigorous, multidimensional understanding of digital agriculture,

thereby allowing thematic findings to be cross-validated with global research trends. This combined approach reveals how determinants, including digital access, institutional capacity, governance frameworks, social capital, and economic incentives, interact cumulatively rather than acting as isolated drivers of adoption.

Furthermore, this review expands existing knowledge by articulating five structured welfare pathways, productivity improvements, market strengthening, risk mitigation, and empowerment, that clarify the mechanisms through which ICT supports farmer well-being. These pathways enhance theoretical understanding by linking ICT adoption not only to behavioural factors but also to economic and institutional processes, providing a more holistic picture than previous reviews that focused predominantly on farmer characteristics or technology attributes [17,22].

In addition, this review differs from prior syntheses by explicitly positioning ICT adoption within a broader governance and welfare-oriented perspective rather than treating digital tools as isolated technical interventions. By integrating institutional, social, and economic dimensions into a single analytical framework, the study highlights how welfare outcomes emerge from the interaction between technology design, policy environments, and collective action. This perspective moves beyond descriptive aggregation of determinants and contributes a more explanatory lens that can inform both academic debate and policy formulation. As such, the review offers not only a consolidation of existing evidence but also a conceptual bridge between digital agriculture research and broader discussions on inclusive development and sustainable transformation.

4.4. Mechanisms Linking ICT Adoption to Welfare Outcomes

Four core mechanisms explain how ICT adoption translates into welfare gains. First, ICT improves information efficiency by reducing search costs and uncertainty, leading to more accurate and timely decision-making. Second, digital tools strengthen coordination within farmer networks, supporting collective learning and problem-solving. Third, institutional reinforcement, through extension services, cooperatives, NGOs, or platform providers, creates enabling environments that enhance the effectiveness of ICT. Fourth, economic incentives shape adoption behaviour when digital tools improve profitability, stabilise prices, or reduce risks linked to climate, pests, or market volatility.

These mechanisms demonstrate that welfare gains arise not only from improved access to information but also from the institutional, social, and economic transformations enabled by ICT. Collectively, these four mechanisms underpin the five welfare pathways identified in this review, explaining how digital technologies translate into productivity gains, stronger market integration, enhanced innovation adoption, improved information access, and broader social empowerment.

Importantly, these mechanisms do not operate in isolation but reinforce one another in shaping welfare outcomes. Improvements in information efficiency enhance farmers' capacity to evaluate risks and opportunities. At the same time, network coordination facilitates the diffusion of knowledge and collective responses. Institutional reinforcement provides continuity and legitimacy to digital practices, ensuring that ICT use is sustained beyond initial adoption phases. At the same time, economic incentives align behavioural change with tangible welfare benefits, making adoption decisions more resilient over time. This interdependence explains why ICT interventions yield more substantial welfare impacts when embedded within supportive institutional and market environments rather than implemented as standalone technological solutions.

4.5. Emerging Technologies and New Analytical Opportunities

Although the reviewed studies do not explicitly incorporate advanced technologies such as digital twins, AI-driven advisory systems, or simulation-based modelling, these emerging tools offer significant potential for future research. Digital twins and AI-enabled decision-support systems can simulate techno-economic outcomes, evaluate sustainability trade-offs, and test the diffusion of innovation across different agricultural, climatic, and governance settings. These tools can help researchers and policymakers anticipate the impacts of digital interventions before implementation, strengthen-

ing evidence-based decision-making.

From an analytical perspective, integrating digital twins and simulation-based approaches offers new opportunities to bridge the gap between empirical evidence and policy experimentation. By creating virtual representations of farming systems, markets, and institutional arrangements, researchers can explore how different ICT configurations perform under varying economic, environmental, and governance scenarios. Such tools enable sensitivity analysis of adoption pathways, allowing policymakers to assess potential trade-offs between productivity, sustainability, and equity before large-scale implementation. This approach is particularly valuable in contexts where field experimentation is costly, time-consuming, or constrained by data limitations.

Moreover, advances in artificial intelligence and data analytics open the door to more adaptive and responsive digital agriculture systems. Machine-learning models can be used to predict heterogeneous adoption behaviour, identify farmer segments most likely to benefit from specific technologies, and support personalised advisory services. When combined with real-time data streams, these tools can enhance early-warning systems, optimise resource use, and improve resilience to climatic and market shocks. However, the effectiveness of such technologies will ultimately depend on governance frameworks that ensure transparency, data protection, and farmer inclusion. Without these safeguards, advanced digital solutions risk reinforcing existing inequalities rather than delivering broad-based welfare gains.

4.6. Critical Reflections, Transferability, and Contextual Boundaries

While this review provides a comprehensive synthesis of existing evidence on ICT adoption and farmer welfare, several critical reflections and contextual limitations warrant careful consideration. First, the geographical distribution of the reviewed studies is uneven. Research from Africa and Asia dominates the empirical literature, while evidence from Europe remains limited and largely policy-oriented. This imbalance reflects broader patterns in digital agriculture research but also constrains the generalisability of findings across diverse agricultural systems and institutional environments.

Second, the transferability of ICT-driven welfare outcomes across regions and jurisdictions should not be assumed. Differences in governance quality, infrastructure availability, market integration, and socio-cultural norms significantly shape how digital technologies are adopted and used. For example, ICT interventions that succeed in contexts with strong extension services and cooperative institutions may yield weaker outcomes in settings characterised by fragmented markets or limited institutional capacity. These contextual dependencies highlight the importance of adapting digital agriculture strategies to local conditions rather than relying on uniform, technology-centred solutions.

Third, the reviewed studies vary considerably in how they define and measure welfare outcomes. While some focus on income, productivity, or efficiency gains, others emphasise social empowerment, resilience, or adaptive capacity. This heterogeneity complicates direct comparison across studies and underscores the need for more standardised welfare metrics in future research. Moreover, short-term welfare gains do not necessarily translate into long-term sustainability, particularly in environments characterized by climatic volatility or policy instability.

Fourth, the increasing reliance on digital platforms raises concerns regarding power asymmetries, data ownership, and platform dependency. Without adequate regulatory oversight, digital agriculture may reinforce existing inequalities by privileging larger or more digitally literate farmers. Smallholders, women, and elderly farmers may face new forms of exclusion if digital systems are not designed with inclusivity in mind. These risks reinforce the need to situate ICT adoption within broader debates on governance, data ethics, and institutional accountability.

Finally, the methodological scope of this review entails certain constraints. Reliance on Scopus-indexed peer-reviewed literature may exclude some regional studies, grey literature, and practitioner-based evidence that could provide additional insights into implementation challenges and informal innovation processes. Although this approach ensures academic rigour and

cross-study comparability, it may underrepresent locally grounded experiences of digital agriculture, particularly in low-resource settings.

Taken together, these reflections emphasise that ICT adoption should be understood as a context-sensitive and institutionally embedded process. Welfare gains emerge not solely from technological availability but from the alignment between digital tools, governance arrangements, and socio-economic realities. Recognising these boundaries is essential for designing digital agriculture interventions that are both effective and equitable.

4.7. Future Research Directions

Building on these insights, several promising avenues for future research emerge. Techno-economic modelling using digital twins and AI-based simulation can provide a deeper understanding of the performance and scalability of digital agriculture interventions. Comparative cross-country studies can clarify how governance arrangements shape adoption patterns and welfare outcomes. Longitudinal evaluations of digital literacy and capacity-building programs are essential to assess the sustainability of behavioural change. Research on data governance, platform accountability, and farmer data sovereignty will become increasingly important as digital ecosystems expand. Machine-learning approaches offer opportunities to predict adoption pathways and identify heterogeneous impacts. Finally, integrating digital agriculture with circular-bioeconomy systems may yield new strategies for sustainable agricultural transformation.

Future research should also pay closer attention to the micro-level behavioural and institutional dynamics that mediate the long-term impacts of ICT adoption. While many studies focus on initial uptake and short-term outcomes, less is known about how digital practices evolve and how farmers adapt, abandon, or modify technologies as economic and environmental conditions change. Investigating these dynamic trajectories can provide more nuanced insights into the sustainability of digital interventions and help distinguish between temporary adoption effects and durable welfare improvements.

In addition, interdisciplinary research integrating agricultural economics, information systems, and institutional analysis will become increasingly important. Such approaches can help bridge the gap between technological innovation and real-world implementation by capturing interactions among markets, governance structures, and social contexts. Greater engagement with participatory and co-design methodologies may further enhance the relevance of future research by ensuring that digital solutions are aligned with farmers' needs and capacities. Together, these directions underscore the need for future studies to move beyond technology-centred perspectives toward more holistic and inclusive models of digital agricultural development.

5. Policy Implications

The findings of this review underscore the importance of developing policy frameworks that promote equitable, scalable, and sustainable digital transformation in agriculture. Notably, the evidence shows that digital technologies do not automatically generate welfare gains; instead, their impacts depend on how digital tools are embedded within broader institutional, economic, and governance systems. In this context, three interrelated policy domains emerge as priorities.

First, infrastructure and digital access. Expanding rural connectivity, ensuring device affordability, and improving electricity reliability remain foundational prerequisites for effective ICT adoption. Evidence from Africa and Asia indicates that welfare benefits from digital technologies materialize only when basic access constraints are addressed. Policies should therefore prioritise last-mile connectivity in rural and remote areas, where market incentives for private investment are often weak. Governments can play a catalytic role by strengthening public–private partnerships for rural network expansion, supporting shared infrastructure models, and introducing targeted subsidy schemes for low-income and smallholder farmers. Without such foundational investments, digital agriculture initiatives risk reinforcing existing inequalities rather than reducing them.

Second, capability strengthening and institutional

support. Beyond access, farmers' ability to use and benefit from ICT depends heavily on digital literacy, learning opportunities, and institutional mediation. The review highlights that capacity-building programs are most effective when they are continuous, adaptive, and locally contextualised rather than delivered as one-off interventions. Strengthening digital extension systems by integrating mobile advisory services, interactive digital platforms, and community-based facilitators can significantly accelerate learning and enhance trust in digital tools. Farmer groups, cooperatives, and local organisations play a crucial role in reducing adoption barriers by facilitating peer learning, collective experimentation, and shared problem-solving. Policies that invest in these institutional arrangements can help ensure that ICT adoption translates into meaningful productivity and welfare gains.

Third, governance, data protection, and economic incentives. As digital technologies become increasingly embedded in agricultural value chains, governance considerations become central to sustainability. Clear regulatory frameworks are needed to protect farmers' data rights, promote transparency in digital platforms, and prevent excessive dependency on proprietary systems. Farmer-centred data governance can strengthen trust and encourage long-term engagement with digital services. At the same time, economic incentives remain critical in shaping adoption behaviour. Instruments such as digital service vouchers, price-information platforms, and ICT-enabled risk management tools can improve the financial viability of digital agriculture, particularly for smallholders operating under high levels of uncertainty.

Policy implementation should also recognise that digital agriculture strategies cannot be uniformly applied across regions with differing levels of digital readiness and institutional capacity. In low-resource settings, incremental and low-cost digital solutions, such as SMS-based advisory services, community radio, or shared digital kiosks, may deliver more immediate welfare benefits than advanced platforms. In contrast, regions with more mature digital ecosystems can prioritise data-driven services, digital traceability, and precision agriculture tools. Tailoring policy instruments to local technological and institutional conditions is essential to avoid mismatches between digital solutions and farmers' actual needs.

Taken together, these policy domains point to the need for integrated, farmer-centred digital ecosystems that balance technological innovation with institutional support and economic inclusion. Digital transformation in agriculture should therefore be viewed not merely as a technological upgrade, but as a coordinated policy process aimed at improving welfare, enhancing resilience, and supporting environmentally sustainable agricultural development.

Finally, effective digital transformation in agriculture requires coordinated policy sequencing across infrastructure development, capacity building, and governance reform. Investments in connectivity must be aligned with training initiatives, institutional strengthening, and regulatory safeguards to ensure that digital tools are both accessible and responsibly used. Fragmented or isolated interventions are unlikely to generate sustained welfare impacts. A systems-oriented policy approach that integrates technological, social, and economic dimensions is therefore critical for translating digital innovation into inclusive and resilient agricultural development.

6. Conclusion

This review provides an integrated synthesis of global evidence on the adoption of Information and Communication Technology (ICT) in agriculture and its implications for farmer welfare. By combining a systematic literature review with bibliometric analysis, the study achieves its three objectives: mapping the evolution of digital agriculture research, identifying the determinants that shape ICT utilization, and clarifying the mechanisms through which ICT adoption influences welfare outcomes. The findings show that the interaction between infrastructure, institutional arrangements, digital capability, and economic incentives drives ICT adoption. The proposed hypothesis, that ICT adoption tends to improve farmer welfare when supported by enabling systems, is broadly confirmed. From an industrial perspective, ICT demonstrates strong economic and environmental relevance by improving production efficiency, strengthening market integration, reducing transaction

costs, and enabling more adaptive and sustainable farm practices.

Beyond synthesizing existing evidence, the study contributes a broader conceptual understanding by linking technological, institutional, and social-capital dimensions within a unified analytical framework. This offers a more comprehensive perspective than earlier reviews that focused narrowly on single determinants or regional cases. Looking ahead, future research should adopt longitudinal and cross-country comparative designs, employ techno-economic simulations using digital twins and artificial intelligence, and explore governance and data-protection models that safeguard farmer autonomy while ensuring equitable and sustainable digital transformation.

Author Contributions

F.S. led the study design, data collection, methodology development, and preparation of the original draft, including writing, editing, and revision. S. contributed to data collection, methodology refinement, and manuscript writing and review. D.S. contributed to methodological development, critical review, and manuscript editing. Z.U. supported methodological validation, manuscript review, and revision. All authors reviewed and approved the final version of the manuscript.

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