

SMART FARMING TECHNOLOGIES AND SMALLHOLDER ADOPTION BARRIERS

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Abstract

Smart farming is increasingly discussed as a route to improve decision-making, input efficiency, climate resilience, and market access in smallholder agriculture. Yet a technology that is technically capable is not automatically usable, affordable, or trusted in a small farm setting. This paper examines the adoption barriers that shape the use of smartphone advisory services, weather and market-information platforms, digital farm records, low-cost sensors, satellite and drone-enabled monitoring, precision irrigation controls, and digital finance tools. It argues that smallholder adoption is best understood as a continuing process rather than a single purchase decision. Farmers must first gain access to a device, network, and service; then interpret the information, test its relevance, manage its cost, seek help when it fails, and decide whether it produces dependable benefits over successive crop cycles. The study presents a literature-informed Smart Adoption Readiness Framework centred on relevance, affordability, connectivity, capability, service support, trust, inclusion, and data safeguards. The framework positions local extension workers, producer organisations, women-led groups, cooperatives, agri-entrepreneurs, repair networks, and transparent service providers as essential parts of the technology ecosystem. A proposed evaluation matrix is included to show how future field studies can measure readiness, continuity of use, confidence, inclusion, technical support, and decision quality without overstating short-term adoption figures. The paper concludes that scalable smart farming for smallholders requires solutions designed for local languages, intermittent connectivity, small plots, shared devices, limited cash flow, and mixed digital skills. Meaningful adoption depends on service bundles and institutional support, not on hardware distribution alone.

Keywords: Smart Farming, Smallholder Agriculture, Digital Agriculture, Precision Farming, Adoption Barriers, Mobile Advisory, Agricultural Extension, Rural Connectivity, Data Governance.

1. INTRODUCTION

Smart farming integrates digital technologies such as sensors, automation, artificial intelligence, geospatial tools, mobile applications, and decision-support systems to improve agricultural decision-making. It includes weather advisories, digital payments, market information, electronic farm records, precision irrigation, satellite imagery, and AI-based crop diagnostics. For smallholder farmers, these technologies are valuable only if they support practical decisions related to sowing, irrigation, input application, pest management, and marketing while complementing local knowledge and extension services.

Smallholder agriculture is highly diverse in terms of landholding, resources, literacy, market access, and climatic conditions. Technologies designed for large commercial

farms may not suit farmers with fragmented land, limited connectivity, shared devices, and inadequate technical support. Successful adoption depends on the relevance, affordability, usability, credibility, and timeliness of digital services rather than technology availability alone (Aker, 2011; Deichmann, Goyal, & Mishra, 2016).

Adoption is further influenced by financial risks, language barriers, unreliable technical support, and concerns over data privacy and service reliability. Therefore, improving smart farming requires addressing technological, economic, social, institutional, and ethical challenges together.

This paper examines major smart farming technologies and the barriers affecting their adoption among smallholders. It proposes a Smart Adoption Readiness Framework that integrates relevance, affordability,

connectivity, capability, service support, trust, inclusion, and data protection to promote practical and equitable agricultural digitalisation.

2. LITERATURE REVIEW

The earliest digital agriculture initiatives in low- and middle-income settings commonly focused on information delivery through radio, mobile phones, short message services, and call centres. Aker (2011) showed that information and communication technologies can lower search costs and expand the reach of agricultural extension, while also noting that information alone does not guarantee use. The value of an advisory depends on the farmer's ability to understand it, judge its credibility, and make a timely response. Deichmann et al. (2016) similarly argued that digital technologies may improve access to information, services, and markets, but they cannot independently resolve credit constraints, weak input systems, insecure land arrangements, or poor roads.

As digital agriculture has advanced, attention has moved from one-way information dissemination toward data-driven platforms and decision-support systems. Smart farming now includes combinations of remote sensing, geographic information systems, sensors, cloud services, automation, data analytics, and mobile applications. Wolfert et al. (2017) described how big data can reshape farm management and agricultural value chains, whereas Klerkx, Jakku, and Labarthe (2019) emphasised that digital transformation also changes advisory relationships, market power, skills requirements, and governance arrangements. These studies show that the social organisation surrounding a technology is as important as the device itself.

Smallholder adoption studies identify a recurring group of constraints: high entry costs; uncertain returns; lack of rural connectivity and electricity; limited digital and data literacy; restricted access for women and marginalised farmers; insufficient local-language content; weak after-sales service; fragmented platforms; and concerns about data ownership. Where tools are designed around small plots and low-resource conditions, adoption may be supported by shared service models, pay-per-use arrangements, cooperatives, producer organisations, local entrepreneurs, and extension partnerships. Fielke, Taylor, and Jakku (2020) further explain that digitalisation changes knowledge and advice networks, requiring extension systems to develop new capacities rather than simply promote applications.

Evidence on mobile agricultural advice also underscores the importance of perceived usefulness. Fabregas, Kremer, and Schilbach (2019) found that successful digital advice needs to be context-sensitive, actionable, and embedded within broader systems of learning and service delivery. Farmers frequently compare digital recommendations with family experience, neighbour feedback, local dealers, and public extension agents before deciding whether to act. This does not indicate resistance to technology; it reflects rational caution when agricultural decisions involve uncertain weather, biological variation, and financial exposure. Adoption research must therefore observe how digital services interact with existing information networks rather than treating them as replacements.

2.1 SUMMARY OF PREVIOUS STUDIES

Author(s)	Method / Focus	Major Findings	Research Gap
Aker (2011)	Review of ICT-enabled agricultural extension	Mobile and communication tools can widen information access, but their value depends on relevance, timing, and user capability.	Limited attention to sensor, platform, and data-governance issues in newer smart-farming systems.
Deichmann et al. (2016)	Digital agriculture in developing countries	Digital tools can lower information and transaction costs but do not remove wider structural constraints.	Needs clearer pathways linking technology use with smallholder service ecosystems.
Trendov, Varas, & Zeng	Global FAO status report	Infrastructure, skills, affordability, policy, and	Calls for locally grounded

(2019)		inclusive access are central to rural digitalisation.	implementation evidence across farming contexts.
Wolfert et al. (2017)	Big-data review in smart farming	Data-enabled tools can improve farm decisions and supply-chain coordination.	Large-farm orientation leaves questions about viable smallholder business models.
Klerkx et al. (2019)	Social-science review of digital agriculture	Digitalisation alters advisory roles, skills, relationships, and governance.	More work is needed on power, equity, and farmer agency in practical deployment.
Fabregas et al. (2019)	Review of digital agricultural advice	Usefulness, customisation, and integration with wider support systems shape impact.	Limited guidance on combining digital advice with hardware and maintenance services.
Fielke et al. (2020)	Review of knowledge and advice networks	Digitalisation reconfigures extension and requires new institutional capabilities.	Needs applied readiness measures for extension and producer organisations.
Smidt & Jokonya (2022)	Adoption factors among small-scale farmers	Cost, infrastructure, awareness, training, and social inclusion influence adoption.	Requires stronger comparison of entry, continuity, and discontinuance stages.

3. OBJECTIVES OF THE STUDY

The primary objective of this paper is to develop a smallholder-centred framework for understanding the adoption of smart farming technologies. The framework examines adoption not only as the purchase or initial registration of a tool, but also as the capacity to use it safely, affordably, repeatedly, and productively over time. It is designed to support future empirical research and programme planning across crop, livestock, horticulture, and mixed-farming contexts.

3.1 PRIMARY OBJECTIVE

The primary objective of this study is to identify the technical, economic, social, institutional, and governance barriers that influence smallholders' ability to adopt and sustain smart farming technologies, and to propose a practical readiness framework for inclusive implementation.

PRIMARY OBJECTIVE POINTS

- To classify smart farming technologies according to their practical relevance for smallholder production and decision-making.
- To examine how affordability, connectivity, device access, language, skills, trust, and service support influence adoption.

- To distinguish initial access from meaningful use, continuity of use, and sustained farm-level value.
- To propose a Smart Adoption Readiness Framework that links technical design with extension, finance, maintenance, and farmer organisations.
- To incorporate inclusion, data privacy, transparency, and farmer agency into the evaluation of digital agriculture projects.

3.2 SECONDARY OBJECTIVES

The secondary objectives focus on implementation conditions that are often overlooked when digital agriculture is assessed only through registration figures, device distribution counts, or application downloads. These objectives direct attention to the support systems that enable farmers to convert access into useful and trusted practice.

SECONDARY OBJECTIVE POINTS

- To identify which smart-farming services are feasible for small plots, shared equipment, seasonal cash flow, and intermittent connectivity.
- To examine the role of farmer producer organisations, cooperatives, local entrepreneurs, and public extension workers in technology mediation.

- To analyse the ways gender, age, literacy, disability, language, and household phone ownership can shape digital access and control.
- To outline support options such as pay-per-use services, demonstration plots, local repair networks, farmer helplines, and assisted onboarding.
- To develop evaluation indicators for relevance, confidence, troubleshooting access, data safeguards, decision quality, and continuation after pilot support ends.
- To identify risks related to incorrect advisories, algorithmic opacity, commercial lock-in, data extraction, and unequal benefit distribution.
- To provide practical recommendations for institutions seeking to design locally legitimate and scalable smart-farming initiatives.

4. RESEARCH METHODOLOGY

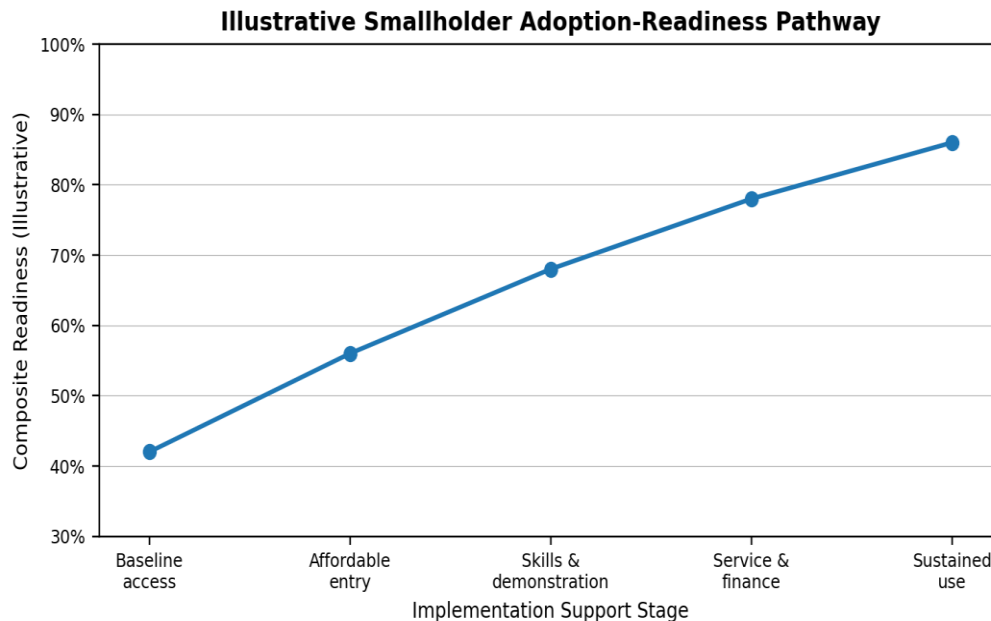
This paper uses an integrative, literature-informed conceptual research design. It brings together scholarship on agricultural extension, digital agriculture, smart farming, adoption behaviour, rural infrastructure, and responsible data practices. The intention is not to claim a new field dataset or a statistically representative adoption rate. Instead, the paper develops a structured framework that can be tested and adapted through future surveys, focus groups, farm observations, service-usage records, and participatory technology trials.

The analysis begins by grouping technologies according to the decision problems they address: information and advisory services; weather and risk management; market, logistics, and financial services; crop and livestock monitoring; water and input management; and farm-record or traceability systems. Each technology category is then examined through eight readiness conditions: relevance to the farm problem, affordability, connectivity and power, user capability, service and maintenance support, trust and evidence of value, inclusion and agency, and data safeguards. These conditions make it possible to evaluate why a tool may be available but not used, or tried once but discontinued.

The proposed framework also uses a staged adoption perspective. In the access stage, the farmer must have a usable device, network connection, local-language interface, and awareness of the service. In the capability stage, the farmer needs confidence to operate the tool, interpret its output, and compare it with trusted local knowledge. In the service stage, advice, hardware, financing, troubleshooting, and feedback must be available when needed. In the continuity stage, the farmer must see sufficient value over more than one production cycle. Finally, the safeguards stage asks whether the system respects consent, data rights, transparency, inclusion, and the farmer's ability to leave or change service providers.

For empirical application, researchers can combine household-level data with service-level data. Household variables may include landholding, crop mix, gender and age of primary decision makers, literacy, device ownership, income stability, access to credit, and membership in producer organisations. Service variables may include price, subscription structure, local-language availability, offline functionality, response time, repair distance, training provision, human support, and data policy clarity. Outcome indicators should include not only registration or purchase, but also frequency of use, confidence, accuracy of interpretation, continuity across seasons, avoided losses, input-decision quality, and perceived fairness.

Figure 4.1: Illustrative Smallholder Adoption-Readiness Pathway



The figure presents a conceptual readiness sequence rather than observed field results. It illustrates how adoption can strengthen when access is combined with affordable entry, practical training, service support, finance, and continued evidence of value.

5. DATA ANALYSIS

Data analysis in a future field application should examine adoption as a sequence of decisions rather than a yes-or-no variable. A farmer who owns a smartphone may not use it for agriculture; a farmer who downloads an app may not follow its recommendations; and a farmer who tries a sensor may stop using it because of cost, repair delays, or uncertain advice. The analysis should therefore combine descriptive indicators with qualitative evidence about motivation, confidence, local relevance, household control over devices, perceived risks, and service experience.

The proposed model compares a stand-alone technology distribution approach with an integrated smallholder support model. The stand-alone approach assumes that access to a device or application is the principal intervention. The integrated model combines relevant technology with local onboarding, live or assisted support, finance or pay-per-use options, extension involvement, demonstrations, repair pathways, and clear information about data use. The second approach is expected to create stronger conditions for meaningful use, but its effectiveness must be tested with actual field data rather than assumed.

For transparency, the numerical values in the following table are illustrative benchmark scenarios included to demonstrate a reporting format. They are not measured results from a controlled trial. Before empirical submission, all figures should be replaced with data from a clearly defined farmer sample, production system, location, adoption period, comparison method, and ethics-approved data-collection process.

5.1 ILLUSTRATIVE EVALUATION MATRIX

Evaluation Metric	Stand-Alone Technology Distribution	Integrated Smallholder Support Model
Technology relevance to farm decisions	65.1%	88.0%

Evaluation Metric	Stand-Alone Technology Distribution	Integrated Smallholder Support Model
Ability to use advisory or decision-support services	57.4%	85.5%
Continuity of use across crop cycles	52.8%	83.7%
Access to repair and troubleshooting	48.9%	81.2%
Women farmers' meaningful access and control	46.5%	78.6%
Farm-record keeping and data interpretation	54.3%	82.4%
Farmer trust in recommendations and service providers	59.2%	86.1%
Quality and timeliness of input-use decisions	61.0%	84.8%
Time to obtain actionable information	76 min	34 min

Note: Values are illustrative benchmark scenarios only. Replace them with measured field data before presenting the work as an empirical study.

6. DISCUSSION

The central implication of this analysis is that smallholder adoption cannot be assessed by counting devices, registrations, downloads, or pilot locations. These measures may capture exposure, but they do not show whether farmers can translate a technology into better decisions. A meaningful adoption measure should ask whether the tool solves a recognised problem, fits local farming calendars, is understandable to the intended user, remains affordable at the time of need, and can be supported when an error or breakdown occurs. This shifts the focus from technology supply toward the conditions of use.

Affordability is more complex than the purchase price. Smallholders may face recurring data charges, electricity costs, subscriptions, replacement parts, calibration needs, transportation to a repair centre, or income loss when a tool fails at a critical moment. Shared and service-based models can reduce these burdens. For example, a cooperative may pool access to a soil-testing device, a local service provider may offer drone scouting on demand, or a producer group may negotiate a lower-cost advisory subscription. Such arrangements can make sophisticated capabilities available without requiring every farm to own the hardware.

Capability and trust are equally important. Digital literacy should not be defined narrowly as the ability to navigate a screen. Agricultural users need to interpret uncertainty, distinguish advisory content from marketing, assess whether a recommendation matches their crop stage, understand when a model may be wrong, and know how to obtain human support. Demonstration plots, farmer-to-farmer learning, extension-worker mediation, helplines, and local-language voice interfaces can make technology more legible. Trust grows when services explain their recommendations, acknowledge uncertainty, respond to feedback, and show evidence from comparable local conditions.

Inclusion requires deliberate design. A service that assumes individual smartphone ownership may overlook women farmers, older farmers, tenant farmers, seasonal workers, and households in which device control is concentrated with one person. Technologies can also increase inequality when data-rich farmers receive better services while those with weak connectivity or low literacy are excluded. Project teams should therefore test who registers, who receives messages, who understands the content, who makes production decisions, and who benefits from any resulting savings or income gains. Participatory design with farmer groups can reveal barriers that application analytics alone cannot show.

Data governance deserves similar attention. Smart farming systems may collect location data, crop records, input purchases, production histories, images, and financial information. Farmers should be able to understand what data are collected, why they are collected, who can access them, how long they are stored, and whether they can opt out. Consent procedures need to be clear, accessible, and appropriate for users with varied literacy levels. Transparent governance can strengthen confidence and reduce the risk that technology adoption creates new forms of dependency or commercial lock-in.

Finally, institutions should support digital agriculture as a long-term service rather than a short-term project. Extension agencies need training in digital advisory and user support, while universities can provide local validation and evaluation. Financial institutions, telecom providers, and technology companies should improve affordable payment models, connectivity, language support, repair services, and interoperable systems. Sustainable smart farming depends on strengthening local service ecosystems and institutional capacity.

7. CONCLUSION

Smart farming technologies can support smallholders through better access to weather information, advisory services, market links, farm records, targeted input use, irrigation decisions, and risk management. Their value, however, depends on more than technical performance. Smallholders require solutions that are relevant to their farming systems, affordable at the point of use, compatible with local infrastructure, understandable in their language, supported by trusted people and repair pathways, and governed in ways that protect their agency and data.

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The Smart Adoption Readiness Framework proposed in this paper offers a practical structure for analysing these conditions. It directs researchers and programme designers to assess relevance, affordability, connectivity, capability, service support, trust, inclusion, and safeguards together. It also distinguishes initial access from continuing, confident, and beneficial use. By doing so, it helps avoid the common mistake of presenting technology distribution or platform registration as proof of adoption.

Future empirical research should test the framework across different regions, crops, farm sizes, gender groups, and service models. Studies should include longitudinal evidence across more than one production cycle, compare individual ownership with shared-service arrangements, evaluate the role of human extension support, and examine how data-governance practices influence farmer trust. Smart farming will be most valuable to smallholders when it strengthens existing knowledge, reduces avoidable risk, expands fair access to services, and remains accountable to the people whose livelihoods depend on it.

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