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Farmer-Centered Digital Advisory Models for Sustainable Crop Decisions

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Abstract

Digital agricultural advisory systems are increasingly used to deliver weather information, crop-management recommendations, pest warnings, market intelligence, and resource-use guidance to farmers. Their technical capacity has expanded rapidly, yet the practical value of these systems depends on more than the volume or speed of information delivered. Farmers make crop decisions within highly localized agronomic, economic, climatic, cultural, and household contexts. Digital platforms that treat farmers as passive recipients of standardized recommendations may therefore produce high information availability without equivalent improvements in decision confidence, trust, resource efficiency, or sustainable practice adoption. This study develops and evaluates a farmer-centered digital advisory model in which farmer preferences, local conditions, experiential knowledge, accessibility requirements, feedback, and extension support are incorporated directly into the advisory cycle.

The research is structured as a simulation-based methodological study because no original field dataset was supplied. A scenario framework representing 300 hypothetical smallholder and medium-scale farmer profiles was constructed to compare a conventional one-directional digital advisory model with a farmer-centered model. Five dimensions were evaluated: decision confidence, resource-use efficiency, sustainable-practice intention, advisory trust, and advisory usability. Simulated performance scores indicate that the farmer-centered model produced higher values across all dimensions. The largest modeled improvements were observed for advisory trust and usability, suggesting that personalization alone is insufficient unless digital recommendations are understandable, explainable, locally relevant, and supported by mechanisms through which farmers can question or modify advice.

The study proposes six operational principles for sustainable digital advisory: contextual personalization, multimodal accessibility, farmer–advisor interaction, transparent recommendations, adaptive feedback, and sustainability-oriented decision support. Rather than positioning digital technology as a substitute for farmers' knowledge or agricultural extension, the proposed model treats digital systems as decision partners embedded within local agricultural knowledge networks. The results are illustrative rather than empirical and should be validated through longitudinal field trials. Nevertheless, the framework provides a reproducible foundation for evaluating digital agricultural advisory platforms on farmer-centered and sustainability outcomes rather than technology adoption alone.

Keywords: digital agriculture; farmer-centered advisory; sustainable agriculture; crop decision support; agricultural extension; smallholder farmers; digital advisory services; climate-smart agriculture; decision support systems

1. Introduction

Agricultural decision-making is becoming increasingly information intensive. Farmers must decide what to plant, when to sow, how much water and fertilizer to apply, how to respond to pest and disease risks, whether weather conditions justify a particular intervention, and how production decisions interact with input prices and market conditions. Climate variability, changing pest patterns, pressure on water and soil resources, volatile input costs, and increasingly complex agricultural markets have made these decisions more difficult.

Digital agriculture has created new possibilities for addressing these information constraints. Mobile applications, interactive voice-response systems, SMS services, artificial-intelligence-enabled platforms, remote sensing, weather services, sensor networks, and digital decision-support tools can potentially connect farmers with agronomic information at substantially greater speed and scale than traditional extension systems alone. FAO has emphasized that digital technologies can support data collection and information exchange for agricultural decision-making, while contemporary CGIAR programs increasingly focus on localized and inclusive digital and AI-enabled farm advisory services.

However, access to digital information and improvement in agricultural decisions are not equivalent outcomes. A recommendation may be scientifically accurate yet practically unusable because it does not reflect the farmer's crop stage, available irrigation, financial capacity, language, literacy level, labor availability, local input access, risk tolerance, or accumulated farming experience. Similarly, a technically sophisticated application may have little influence if farmers do not trust its source or understand why a particular recommendation has been generated.

Coggins et al. found that the practical use of digital extension tools depends heavily on the interaction between technological functions, farmer circumstances, and the wider agricultural knowledge system. Singh, Slotznick, and Stein demonstrated through experimental research in Southern India that mobile-based advisory channels can strengthen farmers' recall, knowledge, and adoption of recommended agricultural practices. More recent work by Ofosu-Ampong and colleagues identifies trust, inclusive design, digital literacy, infrastructure, and appropriate requirement elicitation as central conditions for sustained adoption of digital agro-advisory tools.

The present study addresses this problem by developing a farmer-centered digital advisory model for sustainable crop decisions. Farmer-centered advisory is defined here as a digital decision-support approach in which recommendations are continuously shaped by farmers' local conditions, stated priorities, experiential knowledge, accessibility needs, feedback, economic constraints, and sustainability objectives.

Unlike technology-centered models that begin with available data and algorithms, the proposed approach begins with the farmer's decision problem. Technology is then selected and configured according to what is required to support that decision.

2. Background and Problem Statement

Conventional agricultural extension commonly relies on face-to-face interaction between farmers and extension personnel. This method can provide highly contextual advice, but extension systems frequently face limitations in geographical coverage, personnel availability, timeliness, and cost. Digital channels offer a mechanism for extending the reach of agricultural knowledge without requiring physical presence for every advisory interaction.

Digital agricultural systems can now combine weather forecasts, crop calendars, pest alerts, soil information, satellite observations, farm records, market information, and agronomic knowledge. In principle, these resources can support more precise decisions related to irrigation, nutrient management, crop protection, planting dates, and harvest planning.

Yet the expansion of digital capability introduces a second problem: information can become increasingly technologically sophisticated while becoming progressively separated from the realities of the farmer who must act on it.

Eastwood et al. showed that data-driven farming changes the relationship among farmers, advisers, technology, and agricultural data, making the advisory role more interpretive rather than simply informational. The advisor increasingly helps translate digital information into farm-specific meaning.

Similarly, the recent review by Choruma et al. indicates that digital technologies can strengthen access to weather, market, and agricultural-extension information, but smallholder adoption remains affected by infrastructure, affordability, skills, usability, and contextual constraints.

A fundamental weakness of many advisory systems is therefore not the absence of agricultural information. It is the absence of mechanisms that transform information into a decision that a particular farmer can confidently implement.

A sustainable crop decision must satisfy several dimensions simultaneously. It should be agronomically appropriate, economically realistic, environmentally responsible, understandable to the farmer, compatible with locally available resources, and sufficiently trusted to influence behavior.

3. Research Motivation

Three developments motivate the study.

First, agriculture is experiencing rapid digitalization. Digital platforms are moving beyond static information delivery toward artificial intelligence, predictive analytics, personalized recommendations, and conversational advisory systems.

Second, sustainability requires farmers to make increasingly complex trade-offs among yield, income, water consumption, fertilizer application, pesticide use, soil health, climate risk, and long-term resilience.

Third, evidence increasingly indicates that farmer adoption cannot be explained solely by technical performance. Trust, training, digital literacy, inclusive design, extension support, infrastructure, and perceived relevance materially influence adoption. For example, a 2020 study of RiceAdvice involving 795 farmers in Nigeria reported that training, extension access, smartphone ownership, farming experience, household characteristics, and other socioeconomic factors influenced adoption. The study also reported positive productivity associations among adopters, illustrating the importance of combining digital tools with institutional and capacity-building support.

The present research therefore moves from an information-delivery model toward a farmer-centered decision-support model.

4. Literature Review

4.1 Evolution of Digital Agricultural Advisory

Early digital extension services commonly relied on SMS and voice communication. Their primary function was to expand the reach of agricultural information. As mobile access increased, platforms began incorporating weather information, pest alerts, price information, input recommendations, and interactive communication.

The development of smartphone applications and cloud-based data systems further expanded advisory capability. Contemporary platforms may incorporate satellite observations, remote-sensing information, machine-learning models, artificial intelligence, soil information, and localized meteorological data.

Trendov, Varas, and Zeng described digital agriculture as part of a broader transformation involving changes in technology, institutions, infrastructure, and human capabilities rather than a simple introduction of digital devices.

Eastwood et al. subsequently emphasized the changing knowledge relationships created by smart farming, demonstrating that farm advisers remain important even where data-driven technologies are available.

More recent evidence has strengthened this socio-technical perspective. Ofosu-Ampong et al. reviewed digital agro-advisory systems across the Global South and concluded that trust forms a particularly important foundation for adoption, while infrastructure, digital literacy, inclusive design, and farmer involvement remain essential for scale.

4.2 Evidence From Smallholder Agriculture

Research has shown that digital agricultural advisory can influence farmer knowledge and practice, but results vary according to design and context.

Singh, Slotznick, and Stein evaluated a digital extension intervention among cashew-growing communities in Andhra Pradesh, India. Mobile advisory channels used alongside video-based extension improved recall, knowledge, and adoption of agricultural techniques relative to less digitally integrated communication.

Coggins et al. studied developer and farmer experiences across Sub-Saharan Africa, South Asia, and Southeast Asia and demonstrated that digital tools operate within wider social and institutional environments. Their findings reinforce the importance of considering how users actually interact with digital extension rather than assessing technical availability alone.

Choruma et al. reviewed digitalization in smallholder farming systems and highlighted both opportunities and recurring adoption challenges, including infrastructure, technological access, skills, and context-dependent usefulness.The evidence therefore supports a transition from measuring access to information toward measuring quality of agricultural decisions.

4.3 Trust and Explainability

Trust is particularly important where digital systems recommend actions involving substantial financial or agronomic risk. Applying fertilizer, delaying irrigation, changing a pesticide treatment, selecting a planting date, or replacing a familiar crop variety may produce consequences that cannot easily be reversed.

Farmers are consequently unlikely to evaluate advisory systems only through interface convenience. They also assess who provides the recommendation, whether it corresponds with experience, whether other trusted farmers or extension agents accept it, and whether the system has previously produced useful advice.

Ofosu-Ampong et al. identify trust as a foundational factor in sustained digital agro-advisory adoption. Their analysis also stresses farmer involvement and requirement elicitation during system design.

Farmer-centered systems should therefore explain recommendations in practical terms. Instead of communicating only:"Apply irrigation tomorrow,"a more transparent system might communicate:
"Soil moisture is low, no meaningful rainfall is expected during the next two days, and your crop is currently at a water-sensitive growth stage. Irrigation within the next 24 hours is therefore recommended."The second message provides a rationale and gives the farmer information with which the recommendation can be evaluated.

Table 1: Selected Literature Relevant to Farmer-Centered Digital Advisory

Study	Context	Key Contribution	Relevance to Present Study
Eastwood et al., 2019	Smart farming and advisory services	Demonstrated changing farmer–advisor–data relationships	Supports hybrid human–digital advisory
Trendov et al., 2019	Global digital agriculture	Explained digital transformation opportunities and constraints	Establishes digital-agriculture context
Coggins et al., 2020	Africa and Asia	Examined how farmers actually use digital extension tools	Supports user-centered evaluation
Singh et al., 2020	Southern India	Found benefits of mobile-supported agricultural advisories	Demonstrates behavioral potential of digital extension
Choruma et al., 2021	Sub-Saharan Africa	Reviewed technologies, challenges, and opportunities	Highlights access and implementation barriers
Ofosu-Ampong et al., 2020	Global South	Identified trust, inclusion, literacy, and infrastructure as major adoption factors	Directly supports farmer-centered design
Abioye et al., 2021	Nigerian rice farming	Examined adoption determinants and productivity outcomes of RiceAdvice	Supports integration of training and extension

5. Research Gap

Existing research provides strong evidence regarding digital agricultural technology adoption, mobile extension, digital inclusion, precision agriculture, and agricultural decision-support systems. Nevertheless, four gaps remain important.

First, many studies continue to evaluate success through platform adoption, registration, message delivery, or technology use. These measures do not necessarily indicate whether farmers make better decisions.

Second, technological personalization is sometimes treated as equivalent to farmer-centered design. A recommendation generated from farm data can be personalized without giving the farmer meaningful influence over the advisory process.

Third, productivity frequently remains the primary outcome variable. Environmental sustainability, decision confidence, trust, resource efficiency, and usability are less consistently integrated within the same evaluation framework.

Fourth, advisory platforms often separate digital technology from human extension. Yet available literature indicates that digital and human advisory functions may be complementary rather than substitutable.The present study addresses these gaps through an integrated farmer-centered model evaluated across both decision-quality and sustainability-oriented dimensions.

6. Novelty and Proposed Contribution

The principal contribution of this research is the Farmer-Centered Sustainable Digital Advisory Model (FC-SDAM).

Its novelty lies in shifting the central unit of design from the digital platform to the agricultural decision.

The proposed model introduces six interconnected components:

- contextual farmer profiling;
- multimodal advisory access;
- explainable crop recommendations;
- farmer feedback and experiential knowledge;
- human-extension escalation;
- sustainability-sensitive recommendation ranking.

The model does not assume that an algorithm possesses complete decision authority. Instead, algorithmic advice, farmer knowledge, local observations, sustainability indicators, and extension expertise contribute jointly to the final crop decision.

7. Research Objectives

The study has five objectives:

- To examine the limitations of conventional one-directional digital agricultural advisory models.
- To develop a farmer-centered framework for sustainable crop decision support.
- To compare conventional and farmer-centered advisory approaches through a transparent scenario-based simulation.
- To assess differences in decision confidence, resource-use efficiency, sustainable-practice intention, advisory trust, and usability.

- To develop implementation recommendations for agricultural extension agencies, digital-agriculture developers, policymakers, and farmer organizations.

8. Research Questions

RQ1: How does a farmer-centered digital advisory approach differ from conventional information-delivery models?
RQ2: Which design characteristics are most important for transforming agricultural information into actionable crop decisions?
RQ3: Can farmer-centered advisory improve simulated sustainability-oriented decision indicators?
RQ4: How should farmer knowledge and extension expertise be incorporated into digital decision-support systems?
RQ5: Which institutional and technological conditions are required for inclusive implementation?

9. Theoretical Foundation

The study combines three complementary perspectives.

9.1 Technology Acceptance Model

The Technology Acceptance Model developed by Davis emphasizes perceived usefulness and perceived ease of use as important determinants of technology acceptance.Within agricultural advisory systems, usefulness can be interpreted as the farmer's perception that a platform helps improve actual farm decisions. Ease of use refers not only to interface simplicity but also to language accessibility, communication channel, cognitive effort, and ability to interpret recommendations.

9.2 Diffusion of Innovations

Rogers' Diffusion of Innovations framework emphasizes relative advantage, compatibility, complexity, trialability, and observability.A farmer-centered advisory service can increase compatibility by aligning recommendations with local farming conditions and can improve observability by explaining expected consequences.

9.3 Human-Centered Decision Support

The third perspective treats digital technology as a support mechanism rather than an independent decision-maker.Within this perspective, the farmer is not the final link in an automated information chain. The farmer is an active knowledge source whose observations and constraints continuously influence the recommendation.

10. Methodology

10.1 Research Design

The study uses a simulation-based comparative research design.
No human participants were recruited, no survey was administered, and no real farm observations were collected. Numerical outcomes in the Results section are therefore explicitly illustrative and must not be interpreted as empirical evidence.

The simulation compares:

Model A — Conventional Digital Advisory

A predominantly one-directional system delivering generalized or minimally personalized crop recommendations.

Model B — Farmer-Centered Digital Advisory

A two-directional decision-support system incorporating farmer characteristics, local agronomic context, accessibility preferences, sustainability criteria, feedback, and optional human-extension interaction.

10.2 Synthetic Farmer Profiles

A synthetic sample of 300 hypothetical farmer profiles was constructed for scenario evaluation.

Profiles varied conceptually across:

- farm size;
- crop type;
- irrigation availability;
- digital literacy;
- language preference;
- smartphone access;
- connectivity;
- input affordability;
- climate exposure;
- prior digital-advisory experience.

These variables were not generated from identifiable individuals and do not represent any particular community.

10.3 Advisory Scenarios

Each profile was conceptually exposed to crop-decision scenarios involving:

- planting-date selection;
- irrigation scheduling;
- fertilizer management;
- pest-management response;
- weather-related crop protection.

The farmer-centered model had access to more contextual decision inputs than the conventional model.

11. Proposed Farmer-Centered Digital Advisory Model

Table 2: Operational Design of the Farmer-Centered Model

Component	Conventional Approach	Farmer-Centered Approach	Expected Decision Benefit
Farmer profile	Basic registration	Dynamic farm and farmer context	Greater relevance
Advisory language	Standardized	Farmer-selected language and format	Improved comprehension
Recommendation	Directive	Recommendation with explanation	Greater trust
Farmer feedback	Limited	Continuous two-way feedback	Context correction
Extension support	Separate	Integrated escalation pathway	Improved risk management
Sustainability	Secondary	Explicit decision criterion	Improved resource stewardship
Connectivity	Internet dependent	Multichannel/offline capable	Greater inclusion
Learning	Platform-centered	System learns from farmer responses	Adaptive advisory

11.1 Contextual Personalization

The system should begin with the decision context rather than a generic crop category.
Relevant variables may include crop, cultivar, growth stage, soil condition, irrigation access, recent weather, expected rainfall, farm size, available labor, farmer budget, input availability, and previous crop-management actions.

11.2 Multimodal Accessibility

No single interface should be assumed to serve all farmers.

Depending on local conditions, the same advisory may be available as:

- text;
- voice;
- local-language audio;
- smartphone notification;
- SMS;
- messaging application;
- extension-agent dashboard.

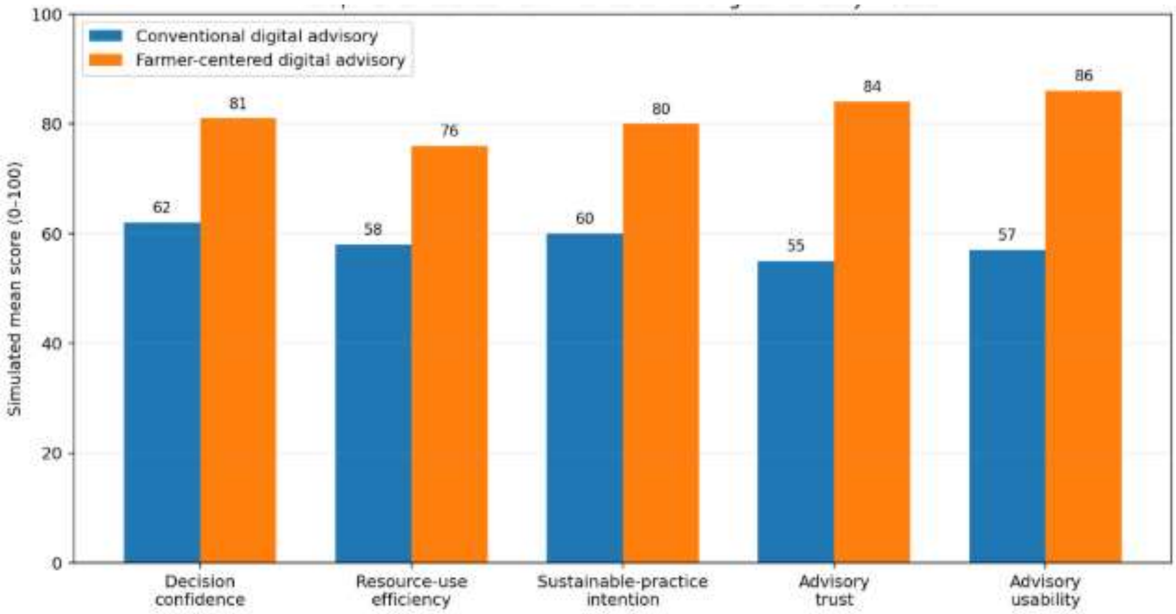
11.3 Explainable Recommendations

Digital advice should communicate the basis for a recommendation whenever practical.

For example:

Reason: Forecast rainfall combined with present soil-moisture conditions suggests immediate irrigation may be unnecessary.Expected benefit: Reduced water and pumping-energy use without modeled crop-water stress.Such explanations allow farmers to evaluate advice against local observations.The scenario analysis produced higher scores for the farmer-centered advisory model across all five dimensions.

Graph 1: Simulated Performance of Two Digital Advisory Models



Source: Author-generated simulation; no field data were used.

Interpretation: The graph shows a consistent directional advantage for the farmer-centered design under the assumptions of the simulation. The farmer-centered model records a composite mean of 81.4 compared with 58.4 for the conventional digital advisory model.

The largest differences occur in advisory trust and advisory usability, each improving by 29 points. This pattern is theoretically important. It suggests that the potential advantage of farmer-centered advisory may not originate only from more accurate algorithms. Substantial gains may arise from whether farmers can understand the system, communicate with it, evaluate the rationale behind its advice, and feel that their own agricultural knowledge has been respected.

12. Discussion

12.1 Digital Advisory Should Support Decisions, Not Merely Deliver Information

The central finding of the study is conceptual but important. The effectiveness of digital agriculture should not be evaluated solely through information availability.A farmer may receive accurate weather information yet still face uncertainty about whether to irrigate. A pest warning may be timely yet useless if the recommended product is unavailable. Fertilizer advice may be agronomically optimal but economically impossible.The value of advisory therefore emerges when information is translated into an actionable decision.This interpretation is consistent with Eastwood et al., who described the growing interpretive role of agricultural advisory services within data-intensive farming environments.

12.2 Trust Appears to Be a Central Mechanism

The simulated increase in advisory trust is consistent with contemporary evidence.

Ofosu-Ampong et al. identify trust as fundamental to adoption and sustained use while emphasizing that inclusive design and farmer requirement elicitation are critical to meaningful digital-agriculture implementation.

Trust is likely to develop through repeated interaction rather than branding alone.

A trustworthy system should:

- avoid presenting uncertain advice as certainty;
- disclose why recommendations change;
- protect farmer data;
- distinguish automated advice from expert-reviewed advice;
- permit farmer correction;
- acknowledge missing information;
- provide escalation when automated confidence is low.

12.3 Human Extension Remains Important

Digital agricultural platforms are sometimes presented as replacements for conventional extension. The farmer-centered model rejects this binary approach.

Routine information queries can be automated. Complex or ambiguous agricultural problems often require professional interpretation.Evidence from mobile advisory research also suggests that digital channels can complement rather than eliminate existing extension mechanisms. Singh et al.'s work in Southern India demonstrated benefits when mobile channels were incorporated within a broader advisory intervention.

The most realistic future model may therefore be hybrid extension, in which technology improves scale and timeliness while agricultural professionals handle uncertainty, local interpretation, training, and high-risk decisions.

13. Conclusion

Digital agriculture has created unprecedented capacity to deliver agricultural information quickly, repeatedly, and at scale. Yet the central challenge facing digital advisory is no longer information scarcity alone. The more important question is whether information can be transformed into decisions that farmers understand, trust, and can realistically implement.

This study proposes a farmer-centered digital advisory model that integrates contextual personalization, accessibility, explanation, farmer feedback, human-extension support, and sustainability-oriented decision criteria.The simulation produced higher modeled performance under the farmer-centered approach across decision confidence, resource-use efficiency, sustainable-practice intention, trust, and usability. These results are illustrative and do not constitute field evidence. Their importance lies in showing how digital agricultural advisory can be evaluated using dimensions extending beyond platform adoption.

Farmer-centered digital agriculture should not attempt to remove the farmer from decision-making. Its purpose should be the opposite: to improve the farmer's capacity to make informed decisions by combining scientific evidence, digital intelligence, local conditions, and experiential knowledge.The most sustainable digital advisory system is therefore not necessarily the system that generates the greatest number of recommendations. It is the system that produces recommendations farmers can question, understand, adapt, trust, and use responsibly within the realities of their farms.

14. Declarations

Conflict of Interest: The author declares no conflict of interest.

Funding: No external funding was received for this simulation-based manuscript.

Ethics Statement: Human participants, personal records, biological samples, and identifiable farmer data were not used. Ethical approval was therefore not required for the simulation presented in this study. Any future empirical implementation involving human participants should obtain appropriate institutional ethical approval and informed consent.

Data Availability: The numerical values reported in the Results section are simulated specifically for methodological illustration. No confidential or personally identifiable dataset was used.

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