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# Strengthening climate-smart agriculture through digital extension: A systematic review of technologies, adoption, and policy implications

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**Abstract**
Climatic-smart agriculture (CSA) provides a strategy to boost productivity, strengthen resilience, and cut greenhouse gas emissions in the face of rising climatic variability. By giving farmers fast, location-specific, and scalable advice, digital agricultural technologies such as mobile and video advisory, remote sensing, Internet of Things (IoT) devices, and AI-based decision support systems have completely transformed extension services. The evidence from 13 peer-reviewed research that looked at the influence of digital technology integration with extension methods on CSA outcomes that published between the periods of 2020 to 2025 are summarized in this study. The results show that while UAV and satellite-based remote sensing improve drought monitoring, irrigation scheduling, and early crop stress detection, mobile and video-mediated alerts greatly increase the adoption of improved agronomic practices. Internet of Things (IoT) automated irrigation and forecasting improve resource efficiency and lead to abatement. Despite these advancements, adoption level still lowered by digital literacy, inadequate infrastructure, high pricing, data reliability difficulties, and unequal access. To address these challenges, inclusive design frameworks, multi-stakeholder engagement, targeted capacity building, and governmental assistance are required. According to the review, properly integrating digital technology with extension services increases CSA implementation while also empowering smallholder farmers, reducing vulnerability to climate risks, and promoting sustainable intensification. These insights can help policymakers, researchers, and practitioners scale digital CSA solutions in a variety of agricultural situations.

**Keywords:** Climate smart agriculture, digital agriculture, decision support system, extension services, technology

## Introduction

Climate change exacerbates weather variability, increases pest pressures, and jeopardizes global food security. The idea of climate-smart agriculture (CSA) highlights three interconnected objectives to solve these issues: increasing productivity, increasing adaptive capacity, and lowering greenhouse gas emissions (Anonymous, 2013). Effective extension and advising services that convert scientific discoveries into practical farming methods are necessary to meet these goals, particularly in smallholder-dominated systems that are susceptible to climate threats (Nannewar *et al*. 2023) [10].

Digital agricultural technology have become revolutionary instruments in this environment. The reach of extension services greatly expanded beyond conventional face-to-face techniques by mobile phones, video platforms, remote sensing, Internet of Things (IoT) devices, and AI-based decision support systems (Li *et al*. 2022) [8]. Digital platforms, in contrast to traditional methods, offer fast, location-specific, scalable advisory that enable farmers to make decisions in real time. Research indicates that when incorporated into extension systems, these technologies enhance water-use efficiency, decrease susceptibility to climate shocks, and hasten the adoption of CSA practices (Abate *et al*. 2023; Belkher *et al*. 2025) [1, 4]. Recent research shows how well mobile-based and video-mediated advisories fill in knowledge gaps. Video and digital advisory platforms improve technology adoption, increase productivity, and lessen knowledge asymmetries, according to randomized assessments conducted in Ethiopia and India (Abate *et al*. 2023; Baul *et al*. 2024; Cole *et al*. 2025) [1, 3, 6].

Additionally, by providing timely alarms for climate threats in South Asia, ICT-enabled early warning systems have proven essential in fostering resilience (Chaudhary *et al*. 2022) [5]. These developments mark a paradigm shift toward digital extension methods that are scalable, farmer-centered, and participatory (Goswami *et al*. 2023; Paliwal & Kumari 2024) [16, 11].

At the same time, CSA's reach being extend by cutting-edge smart agricultural technologies. While UAV-based stress detection allows for early crop management intervention, IoT-enabled irrigation and deficit irrigation systems maximize water-use efficiency in semi-arid environments (Li *et al*. 2022; Kaur *et al*. 2024; Belkher *et al*. 2025) [8, 7, 4]. Although infrastructure and financial constraints continue to be major obstacles, robotics, aquaponics, and machine learning applications provide promise for resource-efficient, sustainable intensification (Raj and Prahadeeswaran 2025) [17]. Extension services for pasture advisories, agricultural stress detection, and drought monitoring are increasingly incorporating remote sensing methods (Tonini *et al*. 2022; Moomen *et al*. 2024; Parra-Lopez *et al*. 2024; Satapathy *et al*. 2024) [14, 9, 12, 20, 13].

Digital agriculture has many obstacles in spite of its potential. Poor infrastructure, a lack of digital literacy, and the requirement for material that is specific to regional languages and cultural contexts are some of the obstacles (Anitei *et al*. 2020; Yuan and Sun 2024) [18, 15]. Unresolved concerns include financial sustainability, data reliability, and inclusivity, especially for women and vulnerable farmers (Choruma *et al*. 2024) [19]. According to Raj and Prahadeeswaran (2025) [17], precise, up-to-date data is essential for warnings to be credible, particularly for weather forecasts and remote sensing results. Inclusive design frameworks, enabling policies, and investments in rural digital infrastructure must overcome these limitations to provide equitable advantages from CSA-driven digital extension systems. (Goswami *et al*. 2023) [16].

This review aims to synthesize peer-reviewed evidence on the role of digital agricultural technologies in strengthening CSA through extension services.

## Materials and Methods

A systematic review approach adopted for this study with random selection of peer-reviewed articles. Searches were conducted in Scopus, Web of Science, and Science Direct using keywords such as "Digital Agriculture," "Climate Smart Agriculture," "Extension Services," "ICT Advisory," and "Remote Sensing Advisory."

### Inclusion criteria were

1. Peer-reviewed journal articles published between 2020 and 2025.
2. Studies evaluating digital technologies integrated with extension or advisory services.
3. Explicit relevance to CSA outcomes (Productivity, Adaptation, Mitigation).

Out of 60 screened articles, 13 m*et al*.l criteria and were analyzed in detail. Each study has coded for technology type, country/region, extension mechanism, and CSA related outcomes.

## Conceptual Framework

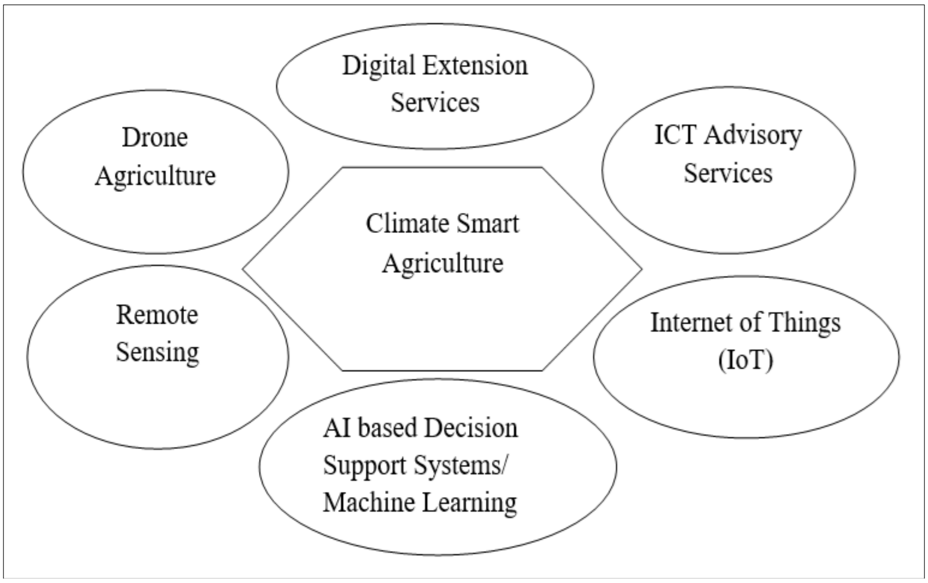


**Fig 1:** Illustrating the digital services provided for boosting climate smart agriculture (CSA)

## Results and Discussion

**Table 1:** Depicting the major results under the review process of various research articles

| Sl. No. | Study Author (s) and Year | Technology/Intervention | Country/Region | Extension/Advisory Element | Key outcome relevant to CSA |
|---|---|---|---|---|---|
| 1 | Abate *et al*. (2023) [1] | Video-mediated extension | Ethiopia | Video + group facilitation | Increased adoption of improved practices |
| 2 | Baul *et al*. (2024) [3] | Video-based group extension | India (Bihar) | Video + human facilitation | Improved adoption and output outcomes for CSA |
| 3 | Cole *et al*. (2025) [6] | Mobile advisory (calls/messages) | India | Personalized mobile calls integrated with extension | Uptake of recommended agronomic practices; resilience to shocks |
| 4 | Belkher *et al*. (2025) [4] | IoT soil moisture sensors | Morocco | IoT system + farmer interface | Improved water-use efficiency while maintaining yields |
| 5 | Parra-Lopez *et al*. (2024) [12, 20] | Remote sensing + DSS | Multi-region | RS + DSS outputs used by extension | Improved drought targeting and irrigation scheduling |
| 6 | Satapathy *et al*. (2024) [13] | Remote sensing-based drought index (RegCDI) | India | RS-based index fed into advisory chains | Improved early-warning capacity and advisories |
| 7 | Chaudhary *et al*. (2022) [5] | ICT early-warning + SMS | South Asia | SMS early warnings via extension | Improved preparedness and timeliness of farmer actions |
| 8 | Moomen *et al*. (2024) [9] | Remote sensing applications | Ghana/West Africa | RS informs extension mapping & advisories | Enhanced targeting and decision support |
| 9 | Kaur *et al*. (2024) [7] | Hybrid IoT + ML irrigation | India (Rajasthan) | Sensor network + ML alerts | Water conservation and automated advisory support |
| 10 | Nannewar *et al*. (2023) [10] | Agrometeorological advisory services | India | KVK + mobile advisories | Improved decision-making, yield, and income outcomes |
| 11 | Li *et al*. (2022) [8] | UAV + remote sensing | China | UAV imagery integrated with extension | Faster detection of crop stress; reduced impact |
| 12 | Tonini *et al*. (2022) [14] | Satellite RS for pasture management | Italy | RS outputs fed into advisory services | Better pasture utilization; drought planning |
| 13 | Paliwal and Kumari (2024) [11] | Multimedia Agricultural Advisory System (MAAS) | India | MAAS integrated into extension | Improved extension responsiveness |

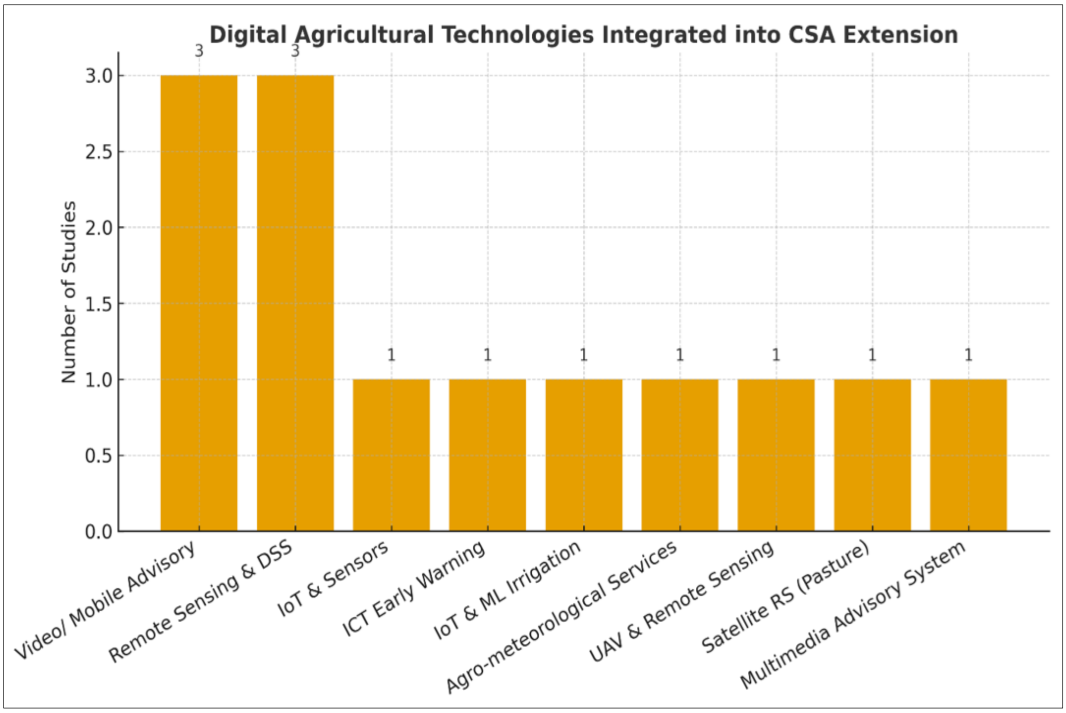


**Fig 2:** Illustrating the digital services shared by the peer-reviewed research articles

**Key points in Discussion**

Digital agricultural technologies have emerged as pivotal enablers of Climate Smart Agriculture (CSA), offering innovative approaches to enhance productivity, adaptation, and mitigation simultaneously. Evidence from 13 peer-reviewed studies indicates that the integration of digital technologies with extension services substantially improves farmer decision-making, adoption of CSA practices, and resource-use efficiency, thereby strengthening climate resilience.

1. **Mobile and Video Advisory Systems:** Empirical evidence demonstrates that mobile and video-based advisory systems significantly enhance the adoption of Climate Smart Agriculture (CSA) practices. Video-mediated extension has been shown to increase farmers' uptake of improved agronomic techniques, while

personalized mobile advisories facilitate resilience to climate shocks by providing timely, location-specific recommendations. These systems are particularly effective in reaching geographically dispersed farmers and scaling CSA practices efficiently.

2. **Remote Sensing and UAV-Based Tools:** Satellite- and UAV-based remote sensing integrated with decision support systems (DSS) provides accurate monitoring of crop health, soil moisture, and climatic stress. Such integration improves drought preparedness, irrigation scheduling, and early detection of crop stress. By converting complex environmental data into actionable advisories, these technologies support both productivity enhancement and climate adaptation while indirectly contributing to mitigation through optimized resource use.
3. **IoT and Smart Irrigation Systems:** IoT-enabled sensors and smart irrigation systems, particularly when combined with predictive analytics or machine learning, enhance resource-use efficiency and farm productivity. These technologies facilitate automated responses to real-time data, thereby reducing vulnerability to climate variability. The efficient application of water and nutrients also contributes to greenhouse gas mitigation, underscoring the relevance of these systems within CSA frameworks.
4. **Agro-meteorological Advisory Services (AAS):** Agro-meteorological advisory services, delivered through both traditional extension channels and mobile/ICT platforms, play a critical role in improving farmers' preparedness and decision-making. By providing timely weather forecasts and seasonal advisories, AAS enhances farmers' adaptive capacity and ensures informed management of climate-related risks.
5. **Integration and Synergy of Technologies:** The evidence indicates that digital technologies are most effective when integrated with conventional extension services, combining automated data-driven advisories with human facilitation. Timely, localized, and culturally relevant recommendations significantly enhance the adoption of CSA practices, strengthen resilience, and improve resource-use efficiency.

**Table 2:** Advanced Technologies in Agriculture and allied sectors (Raj & Prahadeeswaran, 2025) [17]

| Sl. No. | Technology | Essence of Work |
|---|---|---|
| 1 | Autonomous mobile platforms | Handle heavy fruits and perform multiple tasks |
| 2 | GNSS-referenced maps and sensor fusion | Precision navigation beyond crop row following |
| 3 | Nonlinear controllers | Improved traction and minimized slippage in deformable soils |
| 4 | Nonlinear model predictive control | Enhanced trajectory tracking with reduced deviation |
| 5 | Point cloud map-based navigation | Successful orchard navigation at 1.0 m/s |
| 6 | Rabbit feeding robot | Accurate navigation, positioning, and 100% feeding success |
| 7 | Robotics and aquaponics | Offer sustainability but face infrastructure and economic challenges |
| 8 | DNN & IoT | Used for fine-grained monitoring and control in agriculture |
| 9 | DNNs in hydrology | Outperformed models in predicting macro-dispersity |
| 10 | DNNs in stream flow | Estimated dispersion coefficients even in extremes |
| 11 | DNN & ANFIS in geotechnical | Predicted rock strain for engineering design |
| 12 | ML in public health | Used in substance abuse detection and outcome prediction |
| 13 | AI and ML in livestock | Cost reduction and animal health monitoring |
| 14 | Neural model (N2) | Predicted pea seed yield based on multiple factors |
| 15 | Arduino-based irrigation | Solar-powered, automated water level control |
| 16 | Re-circulatory aquaponics | Enhanced herb growth and saved 90% water |
| 17 | Variable rate tech, GPS, ML | Optimized resource use and increased yields |
| 18 | CNN model | Accurate classification of plant leaf diseases |

## Challenges and Constraints

Despite their potential, several constraints limit the widespread adoption of digital agricultural technologies:

1. **Lack of Digital Literacy and Skills:** Many smallholder farmers lacking technical knowledge required for effective utilization of digital advisory platforms. Successful digital agriculture applications need to respect local knowledge and practices, completely take into account the preferences and characteristics of various rural communities and smallholder farmers, and reflect the distinctive sociocultural features of certain locales. Technologists should thus aggressively connect and interact with smallholder farmers (Yuan and Sun 2024) [15].
2. **Infrastructure Limitations:** Inadequate internet connectivity, electricity, and access to devices hinder technology deployment, especially in remote regions. The requirement for region-specific model training, the high upfront expenditures of IoT and sensor-based infrastructure, the lack of technical expertise among farmers, and the restricted availability of high-quality data are some of the main drawbacks. Concerns with system compatibility, data privacy, because the scalability of ML systems in actual farming contexts hampered by the accuracy of forecasts in a variety of agro climatic situations (Raj and Prahadeeswaran 2025) [17].
3. **Content Localization:** Advisories must localized to reflect farmers' real contexts.
   Using local languages ensures clarity and accessibility. Content should match specific agro-climatic conditions. Cultural norms and practices need to respect by contents prepared by them. Such tailoring enhances both relevance and farmer comprehension (Yuan and Sun 2024) [15]
4. **Financial and Operational Sustainability:** High initial costs, maintenance of digital tools, and lack of long-term funding mechanisms restrict scalability (Anitei 2020) [18].
5. **Data Accuracy and Timeliness:** The reliability of advisories binder to the accuracy of data. Real-time information ensures timely and actionable

recommendations. Weather forecasts play a critical role in guiding farm operations. Remote sensing outputs must be precise to support decision-making. (Raj and Prahadeeswaran, 2025) [17].

6. **Inclusivity and Equity:** Ensuring that women, marginalized groups, and resource-poor farmers benefit equally remains a significant challenge (Choruma *et al*. 2024) [19].
7. **Inadequate government policies:** Small-scale farmers' use of digital tools greatly influenced by policy, and without strong policies, digital agriculture may not succeed. First, policy resources are severely lacking in rural areas. The digital transformation of smallholder farmers requires the creation of digital infrastructure and the corresponding distribution of resources**.** **(**Goswami *et al*. 2023) [16].

Addressing these challenges requires multi-stakeholder collaboration, participatory design of advisory systems, targeted capacity-building programs, and robust evaluation mechanisms to ensure that digital extension services effectively support CSA implementation at scale.

**Suggestions to overcome challenges and constraints (Yuan and Sun 2024)** [15]

**1. Lack of Digital Literacy and Skills**

- Put in place farmer-training programs that emphasize usability and local context with an emphasis on digital skills, especially senior farmers.
- Create material in local languages and user-friendly interfaces.
- Make use of "train-the-trainer" and peer-learning approaches, which encourage local lead farmers to instruct others.
- Incorporate technology use modules into local agricultural schools' and extension programs' curricula.

**2. Infrastructure Limitations**

- Make investments in a steady supply of electricity and rural internet connectivity (broadband and mobile network expansion).
- When the grid is unstable, power gadgets with inexpensive, off-grid power sources (like solar).
- Implement public infrastructure initiatives, such as community access centres and ICT hubs.
- In advisories, highlight offline capabilities and low-bandwidth, lightweight solutions.

**3. Content Localization**

- To guarantee linguistic, cultural, and agro climatic relevance, co-design advisories with local stakeholders.
- Use metaphors and examples that are appropriate for the local dialects and translate or modify the content.
- For localization and distribution, make use of community leaders and local extension agents.

**4. Financial and operational sustainability**

- To lower smallholders' initial expenses, implement shared costs or subsidies models backed by donors or the government.
- Create business models that support sustainability (e.g., shared device ownership, subscription).
- Offer financing and microcredit options for maintenanc e and equipment
- Create long-lasting, low-maintenance technology with minimal operational complexity.

**5. Data Accuracy and Timeliness (Parra-Lopez *et al*. 2024)** **[12, 20]**

- Increase the number of local real-time data gathering networks (sensors, weather stations).
- Combine ground truth calibration with satellite/remote sensing.
- Process data quickly and provide forecasts and alerts with little delay by utilizing IoT + AI approaches.
- Create procedures for data source validation and quality control.

**6. Inclusivity and Equity (Nxumalo and Chauke 2025)** **[21]**

Programs should be specifically designed to incorporate low-resource farmers, women, and marginalized groups (e.g. gender-responsive training, targeting).

- To guarantee reach in isolated locations, use community-based solutions.
- Reduced access hurdles (community digital hubs, shared devices, low cost).
- Put in place measures that guarantee fair distribution, such as providing underprivileged populations with subsidized access.

## Conclusion

Whenever modern agricultural technologies combined with extension services, CSA adoption increases significantly, resource efficiency improves, and climate resilience strengthens. Evidence shows that mobile, video, IoT, and remote sensing tools perform best when paired with human facilitation and context-specific advisories. To overcome adoption difficulties, policies must invest in rural digital infrastructure, encourage farmer training, and assure equal access for women and underrepresented groups. Subsidy programs, microcredit, and low-cost technological solutions can help increase in financial and operational viability. Data accuracy, localization, and timely distribution to be addressed using integrated IoT, AI, and remote sensing frameworks. Finally, multi-stakeholder engagement, open architecture, and encouraging policy frameworks are required to grow CSA-driven digital extension systems fairly and sustainably.

## Author's contribution

**First Author:** Conceptualization and Designing of overall core idea of the review article, guide and consulting rest of the authors for improvise.

**Second Author:** Written some of the parts such as Introduction, Suggestions and Conclusion and overall editing, corrections rectifying in the article.

**Third Author:** written some parts of the article, helped to furnish the work such as References, Styling them, and making some figures.

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**Abbreviations**
1. AAS- Agro-meteorological Advisory Services
2. AI- Artificial Intelligence
3. ANFIS- Adaptive Neuro-Fuzzy Inference System
4. CNN- Convolutional Neural Networks
5. CSA- Climate Smart Agriculture
6. DNN- Deep Neural Networks
7. DSS- Decision Support System
8. GNSS- Global Navigation Satellite Systems
9. GPS- Global Positioning System
10. ICT- Information Communication Technology
11. IoT- Internet of Things
12. KVK- KrishiVigyan Kendra
13. MAAS- Multimedia Agricultural Advisory System
14. ML- Machine Learning
15. RS- Remote Sensing
16. SMS- Short Message Service
17. UAV- Unmanned Aerial Vehicle

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