



Plant Archives

Journal homepage: <http://www.plantarchives.org>

DOI Url : <https://doi.org/10.51470/PLANTARCHIVES.2026.v26.no.2.223>

DIGITAL TECHNOLOGIES AND INFORMATION ACCESS FOR THE ECONOMIC TRANSFORMATION OF MILLET PRODUCTION SYSTEMS: A SYSTEMATIC REVIEW

Nethravathi Ashok Patil*, Annapurna Neeralgi, Rajiyabegaum S. Hosalli and M.N. Lavanya

University of Horticultural Sciences, Bagalkot, Karnataka, India.

*Corresponding author E-mail : netravathi.patil@uhsbagalkot.edu.in

(Date of Receiving-10-07-2026; Date of Revision-15-09-2026; Date of Acceptance-25-09-2026)

ABSTRACT

Millet production systems continue to face challenges such as low productivity, limited access to timely agricultural information, weak market integration, and low adoption of modern technologies. Although digital agriculture has advanced rapidly, existing studies have largely examined individual technologies in isolation, providing limited understanding of how integrated digital technologies and information access collectively contribute to the economic transformation of millet production systems. This review addresses this gap by synthesizing evidence on the role of digital technologies in improving productivity, resource-use efficiency, market participation, climate resilience, and farmer livelihoods. Guided by the Agricultural Innovation Systems (AIS) framework and the Sustainable Livelihoods Framework (SLF), a systematic review following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines was conducted using peer-reviewed literature and policy reports published between 2010 and 2026. The review indicates that artificial intelligence, Internet of Things, remote sensing, geographic information systems, mobile advisory platforms, blockchain, and digital marketplaces enhance farm decision-making, reduce production risks and transaction costs, improve market access, and increase farm profitability. However, inadequate digital infrastructure, limited digital literacy, poor internet connectivity, affordability constraints and institutional barriers continue to impede technology adoption among smallholder millet farmers. The review highlights the need for inclusive digital infrastructure, strengthened extension systems, and supportive policy frameworks to accelerate the digital transformation of millet production systems, contributing to sustainable agricultural development and the achievement of the United Nations Sustainable Development Goals, particularly SDG 2 (Zero Hunger), SDG 9 (Industry, Innovation and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action).

Key words : Digital Agriculture, Millet Production Systems, Artificial Intelligence, Precision Agriculture, Information and Communication Technology, Digital Extension, Internet of Things, Remote Sensing, Economic Transformation, Climate-Smart Agriculture, Smallholder Farmers, Agricultural Innovation.

Introduction

Millets are among the oldest cultivated cereals in India and have historically contributed to food security, nutritional well-being, and livelihood sustainability, particularly in rainfed and semi-arid regions (Saleh *et al.*, 2013; Goron and Raizada, 2015; Chandra *et al.*, 2016). Their tolerance to drought, high temperatures, poor soil

fertility, and low external input requirements has resulted in their increasing recognition as climate-smart crops capable of supporting resilient agricultural systems under changing climatic conditions (Chandrasekara and Shahidi, 2011; Yadav *et al.*, 2024; Harish *et al.*, 2024). Compared with rice and wheat, millets generally require less water and perform well under marginal environments, making

them particularly suitable for smallholder farming systems in India's dryland ecosystems (Yadav *et al.*, 2024; Suman and Chandra, 2024). Their importance received renewed international attention following the declaration of 2023 as the International Year of Millets by the United Nations at India's initiative (FAO, 2023).

India is the world's largest producer of millets, contributing approximately 40–44% of global millet production and possessing a substantial share of the global cultivated area under these crops (Harish *et al.*, 2024). Major millet-producing states include Rajasthan, Karnataka, Maharashtra, Uttar Pradesh, Madhya Pradesh, Tamil Nadu, Telangana, Andhra Pradesh, Gujarat, and Odisha. Millets are an important source of food and income for millions of resource-poor and farming households. Although millet cultivation declined in several regions following the expansion of rice and wheat during the Green Revolution, productivity has improved through better cultivars, crop management practices, research, and institutional support. Nevertheless, the gap between actual and attainable productivity indicates considerable scope for technological and institutional interventions.

The Government of India has introduced several initiatives to promote millet cultivation, processing, consumption, and exports. Programmes such as the National Food Security Mission–Nutri Cereals, National Mission on Sustainable Agriculture, Rashtriya Krishi Vikas Yojana and other millet initiatives have strengthened research, seed systems, extension, and value-chain development. At the same time, growing consumer awareness of nutrient-rich, gluten-free, and functional foods has increased demand for millet-based products, creating opportunities for farmers, processors, entrepreneurs and agribusinesses (Jindal and Nikhanj, 2023; Harish *et al.*, 2024). However, millet production systems continue to face fragmented landholdings, climate variability, inadequate extension, weak market linkages, limited mechanization and poor access to timely agricultural information.

Digital transformation provides an important opportunity to address these constraints. Artificial intelligence (AI), the Internet of Things (IoT), remote sensing, Geographic Information Systems (GIS), unmanned aerial vehicles (UAVs), cloud computing, blockchain, big-data analytics, and mobile-based advisory services are changing agricultural information generation and decision-making (Wolfert *et al.*, 2017; Klerkx *et al.*, 2019; Javaid *et al.*, 2023). These technologies enable monitoring of crop growth, soil moisture, nutrient status, weather conditions, pest outbreaks, and market prices, thereby supporting precision agriculture and improved

farm management.

Information access is a critical determinant of agricultural productivity and economic performance. Timely information on weather, pests and diseases, crop management, inputs, credit, insurance, government schemes, and market prices enables farmers to make better production and marketing decisions while reducing uncertainty and transaction costs (Aker, 2011; Fabregas *et al.*, 2019). Digital extension platforms, mobile applications, interactive voice-response systems and social media-based advisory services have expanded the reach of agricultural extension beyond conventional face-to-face systems.

Despite these developments, adoption of digital technologies among millet-growing households remains uneven. Smallholders face inadequate connectivity, limited smartphone ownership, insufficient digital literacy, affordability constraints, language barriers, and weak institutional coordination. These constraints are particularly important in rainfed, tribal, and economically disadvantaged areas where millet cultivation is concentrated. Consequently, disparities remain in access to and use of digital agricultural services.

Although, considerable research has examined AI, precision agriculture, mobile advisory systems, blockchain, remote sensing and digital marketing, most studies investigate these technologies independently or focus on major crops rather than millet production systems. Existing millet reviews have primarily emphasized nutrition, agronomy, processing, climate resilience and health benefits, with comparatively limited attention to the integrated role of digital technologies and information access in transforming millet economics.

Against this background, the present systematic review synthesizes evidence on digital technologies and information access for the economic transformation of millet production systems in India. The review aims to: (i) examine digital technology adoption in millet farming; (ii) evaluate the role of digital information systems in productivity, resource-use efficiency, and market participation; (iii) assess impacts on farm income, value-chain development, and livelihood resilience; (iv) identify technological, institutional and socio-economic barriers; and (v) propose research priorities and policy interventions for inclusive and economically sustainable digital millet production systems.

Digital Transformation of Indian Agriculture

Digital transformation has become an important component of agricultural modernization in India. ICTs, AI, IoT, remote sensing, cloud computing, blockchain,

and big-data analytics have supported a transition from conventional input-intensive farming towards data-driven and knowledge-based systems (Wolfert *et al.*, 2017; Klerkx *et al.*, 2019). Digital agriculture is not limited to technology adoption; it also transforms agricultural knowledge systems, institutions, governance arrangements and value chains through real-time information exchange.

India's digital agricultural development has been supported by initiatives including Digital India, the Digital Agriculture Mission, AgriStack, e-NAM, PM-KISAN, and the Soil Health Card Scheme. These initiatives have expanded mobile advisory services, digital records, precision farming tools, financial services and electronic markets. However, adoption remains unequal because of fragmented landholdings, low digital literacy, inadequate rural infrastructure, and differences in internet access.

The literature emphasizes that digital transformation is a socio-technical process involving farmers, extension agencies, research institutions, private enterprises, and policymakers. Klerkx *et al.* (2019) noted that digitalization affects innovation systems, farmer–institution relationships, governance and value chains. Therefore, technological investment must be accompanied by institutional support, capacity building, appropriate policies, and inclusive access mechanisms.

Information Access and Agricultural extension

Timely and reliable agricultural information is essential for productivity, profitability, and climate resilience. Information asymmetry can constrain decisions related to input use, pest control, crop management, marketing, and climate adaptation. ICT-based extension has emerged as an important mechanism for reducing these information gaps (Aker, 2011; Fabregas *et al.*, 2019).

The expansion of mobile telephony and internet connectivity has transformed extension from predominantly face-to-face systems towards digital advisory systems. Mobile applications, SMS, interactive voice response systems, WhatsApp groups, and platforms such as Kisan Suvidha and e-NAM provide weather forecasts, market prices, soil information and pest management recommendations.

Digital extension can improve technology adoption, reduce production risks and strengthen market participation. However, effectiveness depends on literacy, language accessibility, trust, quality of information, affordability, and institutional support. Women farmers, tribal communities, elderly farmers and resource-poor households may experience greater barriers to digital

access (Goswami *et al.*, 2023).

Artificial Intelligence, Internet of Things, GIS, Drones, and Precision Agriculture

AI, IoT, GIS, remote sensing, drones, machine learning, and precision agriculture have created opportunities for site-specific and data-driven farming. Precision agriculture uses spatial and temporal information obtained from sensors, satellites, drones and field observations to improve farm management (Wolfert *et al.*, 2017; Bertoglio *et al.*, 2021).

AI applications include disease diagnosis, pest prediction, yield forecasting, nutrient management, irrigation scheduling, and market forecasting. IoT sensors continuously monitor soil moisture, temperature, humidity, and crop conditions. Drones provide high-resolution imagery for crop surveillance, stress detection, weed mapping and precision input application. GIS and remote sensing support spatial planning, crop mapping, drought monitoring and resource assessment.

However, adoption among smallholders remains limited because of high costs, fragmented landholdings, inadequate infrastructure, technical complexity, and lack of skilled personnel. Consequently, many applications remain concentrated in research projects, pilot programmes, and commercially oriented farming systems.

Digital technologies in Millet Production systems

Compared with rice and wheat, digital technology applications in millet production have received limited scholarly attention. Existing millet research has largely focused on crop improvement, nutrition, climate resilience, agronomic management and value addition (Saleh *et al.*, 2013; Goron and Raizada, 2015).

Emerging evidence indicates that digital advisory platforms can provide location-specific recommendations on sowing dates, nutrient management, pest management, irrigation and weather-related risks. GIS and remote sensing can support millet acreage mapping, drought monitoring, and yield estimation. AI-based systems have potential for disease detection and nutrient-deficiency identification.

ICAR, ICRISAT and other research organizations have emphasized the integration of digital advisory services with improved seed systems, climate information, and market intelligence. Nevertheless, empirical evidence concerning the economic effects of these technologies in millet production remains limited.

Economic Impacts of Digital Agriculture

Digital technologies can contribute to agricultural development by increasing productivity, reducing costs,

improving profitability, and strengthening market participation. Digital decision-support systems improve the allocation of water, fertilizers, pesticides, and labour, while digital marketplaces increase price transparency and market access (Wolfert *et al.*, 2017 and Klerkx *et al.*, 2019).

Blockchain and digital traceability can improve transparency, quality assurance, food safety, and export competitiveness. AI-based analytics can strengthen risk management through improved weather forecasting, pest surveillance, and market intelligence.

However, benefits differ according to farm size, income, education, infrastructure and institutional conditions. Smallholders often experience lower adoption because of financial and technical constraints. Inclusive policies, digital infrastructure, farmer training, and affordable technologies are therefore necessary.

Research Gaps and Conceptual Framework

Several research gaps emerge from the literature. First, existing research frequently examines AI, IoT, remote sensing, blockchain, or digital extension separately, with limited attention to integrated digital ecosystems. Second, comparatively little empirical evidence is available for millet production systems, as most studies focus on rice, wheat, cotton and horticultural crops.

Third, limited evidence exists on long-term impacts of digital technologies on farm income, employment, market participation, livelihood resilience and sustainability among millet-growing households. Fourth, the interaction between digital infrastructure, digital literacy, institutional support, and adoption remains insufficiently examined among tribal and resource-poor communities.

The conceptual framework therefore considers digital infrastructure, information accessibility, precision agriculture, digital extension, and institutional support as enabling factors. These influence technology adoption, farm decision-making, resource-use efficiency, market integration and value-chain development. These intermediate outcomes can subsequently contribute to higher productivity, improved income, climate resilience, and sustainable economic transformation of millet production systems.

Methodology

This study adopts a systematic literature review (SLR) approach to synthesize evidence on digital technologies and information access in the economic transformation of millet production systems in India. SLR provides a transparent and reproducible process for identifying, evaluating and synthesizing scientific evidence

while reducing selection bias (Tranfield *et al.*, 2003; Kitchenham and Charters, 2007).

The review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) framework (Page *et al.*, 2021). The methodological process includes identification of relevant literature, screening of studies, assessment of eligibility, extraction of relevant information and thematic synthesis. The review focuses on digital agriculture, agricultural extension, information access, AI, IoT, GIS, remote sensing, drones, precision agriculture, digital markets and economic outcomes relevant to millet production.

Results

Digital Transformation of Indian Agriculture

The reviewed literature demonstrates that digital transformation has become a major driver of agricultural modernization in India. ICTs, AI, IoT, remote sensing, cloud computing, blockchain and mobile advisory systems are enabling a transition towards data-driven farm management (Wolfert *et al.*, 2017; Klerkx *et al.*, 2019).

Government initiatives including Digital India, Digital Agriculture Mission, AgriStack, NeGPA, e-NAM, PM-KISAN and the Soil Health Card Scheme have strengthened the digital agricultural ecosystem. These initiatives aim to improve digital service delivery, agricultural databases, market access, advisory services and financial inclusion.

Mobile-based advisory systems are among the most widely used digital technologies. Aker (2011) emphasized their role in reducing communication and information costs, while Fabregas *et al.* (2019) found that digital advisory services can improve technology adoption and farm management when information is timely and location-specific. Platforms such as Kisan Suvidha, mKisan and Kisan Call Centres provide weather, pest, soil, and market information.

Information access also improves market participation. BIRTHAL *et al.* (2015) reported that ICTs can reduce transaction costs and improve farmers' bargaining position. AI and big-data systems offer additional opportunities for yield prediction, pest diagnosis, irrigation management, and precision nutrient application, although their use remains concentrated in pilot and commercial settings.

IoT enables continuous monitoring of soil and crop conditions, while GIS and remote sensing provide information on crop health, drought, and acreage. Combining these technologies can support precision agriculture and evidence-based management.

Government investment in digital infrastructure has therefore become an important foundation for agricultural transformation.

However, the digital divide remains a major concern. Education, income, farm size, digital literacy, smartphone ownership, connectivity and technical support influence adoption. Remote, tribal and rainfed regions often face greater barriers. Digital technologies therefore need to complement rather than completely replace traditional extension services.

Digital technologies also have an important role in climate resilience. AI-based forecasting, remote sensing, GIS and digital advisories can help farmers respond to drought, heat, erratic rainfall, pest outbreaks, and other risks. This is especially relevant to millet systems because of their concentration in rainfed and drought-prone areas.

Blockchain and traceability systems offer potential for improving supply-chain transparency, quality assurance, food safety and market confidence. Nevertheless, evidence regarding their practical application in Indian millet value chains remains limited.

Overall, the evidence indicates that digital transformation can improve information access, farm management, market integration and climate resilience. However, the benefits remain uneven and millet-specific evidence is still inadequate.

Evolution of Agricultural Extension in India

Agricultural extension in India has evolved from conventional face-to-face approaches towards digitally enabled systems. Traditional methods included demonstrations, field visits, farmer meetings, and printed materials. Although, these contributed significantly to agricultural development, their reach was limited by inadequate personnel, financial resources and geographical constraints (Swanson and Rajalahti, 2010).

The expansion of ICTs has enabled extension agencies to reach larger numbers of farmers more rapidly. National initiatives such as NeGPA, Digital Agriculture Mission, Kisan Call Centres, mKisan, Kisan Suvidha, e-NAM and AgriStack have strengthened digital information delivery.

a) Digital Information Sources for Farmers :

Mobile phones have become a major source of agricultural information. Farmers use mobile technologies to obtain market prices, weather forecasts, crop recommendations, pest information, and government-related information. Smartphones have further expanded access by integrating multiple agricultural services within single platforms.

Studies indicate that mobile advisory systems are most effective when recommendations are localized and

supported by interpersonal extension. Digital tools therefore work best as complementary components of broader extension systems.

b) ICT-Based Extension and Technology

Adoption : The literature indicates a positive relationship between ICT-based extension and technology adoption. Digital information can improve awareness and adoption of improved seeds, fertilizers, irrigation and pest management practices (Aker, 2011; Fabregas *et al.*, 2019). Regular access to ICT services can reduce uncertainty associated with production decisions and improve farmers' capacity for evidence-based management.

Information access also contributes to better market participation by improving price discovery and reducing transaction costs. Thus, digital extension contributes not only to technology dissemination but also to economic decision-making.

c) Role of Digital Platforms in Agricultural

Information Delivery : e-NAM has strengthened agricultural market transparency through electronic trading and price information. The mKisan Portal provides location-specific advisories through SMS, while Kisan Call Centres provide technical guidance.

AgriStack seeks to integrate farmer information, land records, crop data, satellite information, and advisory systems into a digital ecosystem. Such integration can support precision agriculture, targeted services, digital credit, and insurance. Integrated platforms can also strengthen coordination among farmers, extension organizations, financial institutions, agribusinesses and policymakers.

d) Information access for Millet Farmers :

Specific research on digital information access among millet farmers remains limited. Millet producers continue to depend on KVKs, FPOs, public extension agencies, NGOs, progressive farmers, and research institutions. Digital advisory services have improved awareness of improved varieties, nutrient management, pest management, weather information, and value addition, but geographical coverage remains uneven.

Compared with rice and wheat, millet-specific digital extension remains underdeveloped. Greater integration of digital advisory systems with seed systems, climate information, and market intelligence is required.

f) Socio-economic Factors Influencing

Information Access : Education, farm size, income, age, smartphone ownership and digital literacy influence access to agricultural ICTs. Women farmers, tribal

communities, elderly farmers and resource-poor households may face greater constraints because of limited device ownership, financial limitations and inadequate digital skills.

Language is another important barrier. Digital agricultural applications need greater support for regional languages and location-specific information to ensure inclusive access.

g) Institutional Support for Digital Extension : Institutional capacity is critical to successful digital extension. Digital tools cannot replace effective extension organizations without adequate human resources, technical support, training, and coordination. Partnerships among government agencies, agricultural universities, research institutions, agritech companies, NGOs, and FPOs can strengthen digital extension.

KVKs can play an important role by combining digital tools with demonstrations, farmer training and climate advisory services. This blended model can improve both the reach and effectiveness of extension.

h) Challenges Limiting Information Access : The major constraints identified are inadequate broadband connectivity, unreliable electricity, poor mobile network coverage, low smartphone ownership, digital illiteracy, limited technical support, fragmented extension systems, affordability constraints, and insufficient localized content. Klerkx *et al.* (2019) emphasized that digital transformation requires investment in infrastructure, institutional reforms, and capacity building.

Fabregas *et al.* (2019) further suggested that digital advisory services generate stronger impacts when integrated with traditional extension, farmer training, and continuous technical support.

Artificial Intelligence (AI), Internet of Things (IoT), GIS, Drones and Precision Agriculture

The review shows that AI, IoT, GIS, remote sensing, drones, machine learning, cloud computing, and precision agriculture are enabling site-specific and climate-smart farming. Their applications are more developed in major crops than in millet systems.

Artificial Intelligence in Agriculture

AI supports predictive analytics, disease diagnosis, pest detection, yield forecasting, nutrient management, and irrigation scheduling. Machine learning and deep-learning techniques can classify crop diseases using digital images and integrate weather, soil, satellite and management data for yield prediction (Kamilaris and Prenafeta-Boldú, 2018; Javaid *et al.*, 2023).

In India, AI-based agricultural decision-support systems are being developed through research institutions, agricultural universities, and agritech companies. However, high costs, poor infrastructure, and limited technical capacity restrict adoption among smallholders.

Internet of Things (IoT) and Smart Farming

IoT systems combine sensors, communication networks and cloud platforms to monitor soil moisture, temperature, humidity, rainfall, and crop growth. Smart irrigation can reduce unnecessary water use, while sensor-based nutrient management can improve fertilizer efficiency.

IoT is particularly relevant to millet farming in drought-prone areas. However, high installation costs, poor connectivity, maintenance requirements and limited technical support restrict adoption. Most millet-related IoT applications remain at the pilot stage.

Geographic Information Systems (GIS) and Remote Sensing

GIS and remote sensing provide spatial information on soil, land use, crop health, rainfall, and climatic conditions. Satellite imagery and vegetation indices such as NDVI can support acreage estimation, drought monitoring, yield forecasting, and crop-stress assessment (Mulla, 2013; Bertoglio *et al.*, 2021).

For millet production, geospatial technologies can identify millet-growing areas, drought-prone regions, and suitable agro-climatic zones. However, direct farmer use remains limited because of technical complexity and dependence on institutional support.

Drone Technology in Agriculture

Drones provide high-resolution imagery for crop monitoring, disease detection, weed mapping, nutrient assessment, and precision spraying. Multispectral imaging can identify crop stress before it becomes visible through conventional field inspection.

In India, agricultural drones are increasingly promoted for spraying, crop monitoring and mapping. However, equipment costs, regulatory requirements, technical skills, and fragmented landholdings restrict individual ownership. Custom hiring centres, FPOs and service providers may provide more practical access for smallholders.

Precision Agriculture Technologies

Precision agriculture integrates AI, IoT, GIS, drones, GPS, and data analytics to apply inputs according to field variability. It can improve productivity and resource-use efficiency by optimizing fertilizer, irrigation, pesticides, seed rates and labour.

The reviewed literature identifies potential benefits including increased productivity, reduced input use, improved irrigation efficiency, better soil monitoring, lower production costs and improved environmental sustainability. Nevertheless, high investment costs, limited infrastructure, and insufficient technical knowledge remain major barriers.

AI and Digital Technologies in Millet production systems

Digital technologies in millet systems remain at an emerging stage. ICAR–Indian Institute of Millets Research and ICRISAT have promoted digital advisory, weather-based information, drought monitoring, precision nutrient management and crop monitoring. AI-assisted disease diagnosis, IoT-based soil monitoring, GIS-based drought mapping, and drone-based crop surveillance show potential.

However, most applications remain experimental or pilot-based. Greater research is required to develop affordable and farmer-friendly millet-specific technologies.

Constraints to Adoption

Major constraints include high investment costs, fragmented holdings, inadequate broadband, limited electricity, poor digital literacy, insufficient technical support, lack of localized content, data privacy concerns and weak institutional coordination.

Successful digital transformation therefore requires technology to be integrated with infrastructure development, farmer training, institutional capacity, governance mechanisms and appropriate extension systems.

Digital Advisory Services for Millet farmers

Mobile-based advisory services represent one of the most accessible digital technologies for millet growers. They provide information on sowing, variety selection, nutrient management, pest control, irrigation, weather, and post-harvest practices (Aker, 2011; Fabregas *et al.*, 2019).

ICAR–IIMR and ICRISAT have demonstrated the potential of digital advisory systems to improve awareness of improved varieties, seed treatment, nutrient management, IPM, climate information and value addition. Farmers receiving timely and localized information can adopt improved practices more effectively.

Artificial Intelligence for Millet crop management

AI can support millet disease diagnosis, nutrient-deficiency detection, weed recognition, yield forecasting,

and climate-risk assessment. Machine learning and CNN-based image analysis have demonstrated potential for disease identification in finger millet and pearl millet.

AI-based growth models can integrate weather, soil, satellite, and management information for yield prediction. However, large-scale adoption remains limited because of inadequate infrastructure, technical skills and high implementation costs.

Internet of Things (IoT) and Smart Millet farming

IoT sensors can continuously monitor soil moisture, temperature, rainfall, humidity, and crop growth. In water-limited millet environments, soil-moisture monitoring can support more efficient irrigation and reduce unnecessary water application.

Nevertheless, unreliable connectivity, installation costs, maintenance requirements and limited technical support remain barriers. Wider adoption requires affordable sensors and appropriate farmer training.

Remote Sensing and GIS Applications

Remote sensing and GIS can support millet acreage estimation, vegetation monitoring, drought assessment, yield forecasting and agro-climatic planning. These technologies can strengthen evidence-based planning by research institutions and policymakers, although their direct use by farmers remains limited.

Drone Technology for Millet production

Drone-based multispectral imaging can identify crop stress, nutrient deficiencies, pests, weeds and disease symptoms. Drones can also support precision spraying and crop mapping. Their application in millet cultivation remains limited and is mainly associated with research institutions, service providers and custom hiring centres.

Precision Agriculture in Millet Systems

Precision agriculture can optimize seed rates, nutrient application, irrigation and weed management according to field conditions. Precision nutrient and irrigation management can improve input efficiency and water productivity. However, fragmented holdings, high equipment costs, and limited technical expertise constrain adoption.

Digital Technologies across the Millet Value chain

Digital transformation extends beyond production to processing, marketing, logistics, and value addition. e-NAM can improve price information and market connectivity, while blockchain can strengthen traceability and quality assurance.

E-commerce and social media provide opportunities for FPOs, SHGs, and rural entrepreneurs to market millet

flour, ready-to-cook mixes, breakfast cereals, cookies, noodles, and other value-added products directly to consumers. Digital payments and online logistics further support commercialization.

Adoption constraints

The principal barriers include inadequate digital infrastructure, poor internet connectivity, limited smartphone ownership, low digital literacy, fragmented holdings, high investment costs, insufficient localized advisory content and weak institutional coordination. A major limitation is the scarcity of millet-specific digital solutions compared with those developed for rice, wheat, cotton, and horticultural crops.

Economic Impacts of Digital agriculture

The reviewed literature indicates that digital agriculture can improve productivity, resource-use efficiency, market integration, profitability, and rural livelihood opportunities. AI, IoT, GIS, remote sensing, drones, blockchain, mobile advisory systems, digital finance, and electronic marketplaces contribute to a transition towards knowledge-driven farming.

Digital agriculture and Farm productivity

Digital technologies improve productivity through timely decision-making, precise input management, continuous monitoring, and early risk detection. AI can support disease prediction, yield forecasting, irrigation scheduling and nutrient management. IoT-based irrigation systems can improve water-use efficiency, while precision nutrient management can reduce fertilizer wastage.

For millet production, weather advisories, nutrient recommendations and IPM information can improve adoption of scientific practices and production stability under rainfed conditions.

Improvement in Farm Income and profitability

Digital agriculture can improve farm income through higher yields, lower production costs, better market prices, and reduced post-harvest losses. Digital advisory services improve production decisions, while digital market information strengthens bargaining power and reduces dependence on intermediaries (Birthal *et al.*, 2015; Fabregas *et al.*, 2019).

FPOs can benefit from digital collective marketing, online procurement, price discovery, and direct consumer connections. In millet value chains, e-commerce provides opportunities to market processed products and capture greater value.

Resource-Use Efficiency and Cost reduction

Precision agriculture enables farmers to apply fertilizers, pesticides, water, and labour according to crop requirements. AI and IoT can improve irrigation scheduling, while drone-assisted spraying can reduce chemical use and labour requirements.

Digital disease and pest monitoring can reduce yield losses through early intervention. For rainfed millet, weather-based information can improve sowing decisions, nutrient application and water management.

Digital Marketplaces and Market Integration

Digital marketplaces improve price transparency, market access, and competition. e-NAM provides opportunities for electronic trading and price discovery, while digital market information can reduce transaction costs and dependence on intermediaries.

Blockchain can improve traceability, food safety and supply-chain transparency. Digital marketing and social media can connect FPOs, SHGs, and rural entrepreneurs with urban consumers and premium markets for value-added millet products.

Digital Financial Inclusion

Digital payments, mobile banking, online credit, digital insurance, PM-KISAN, DBT, Aadhaar-enabled payments and UPI have strengthened financial transactions in agriculture. Digital financial services can reduce transaction costs and improve access to credit, insurance and government benefits.

Digital credit assessment using land records, satellite information, and production history may facilitate faster credit decisions. However, digital financial inclusion also depends on literacy, connectivity, trust and institutional support.

Employment generation and Rural entrepreneurship

Digital agriculture creates employment in areas such as drone operation, GIS analysis, AI services, data management, digital extension, agritech entrepreneurship, e-commerce, logistics, and precision farming.

Digital platforms can also support rural youth, women, FPOs and SHGs in establishing enterprises around millet processing, value addition, packaging, branding, and online marketing. Thus, digitalization can diversify rural employment beyond primary production.

Climate Resilience and Economic sustainability

Digital technologies improve climate resilience through weather forecasting, drought monitoring, remote sensing, GIS, IoT and climate-smart advisory services.

Early warning systems can help farmers respond to drought, heat stress, erratic rainfall, floods and pest outbreaks.

For predominantly rainfed millet systems, climate advisories can improve sowing decisions, promote drought-tolerant varieties and encourage water conservation. These interventions can reduce production risks and improve economic stability.

Economic constraints Limiting Digital Agriculture

Despite potential economic benefits, adoption is constrained by high investment costs, poor broadband, inadequate electricity, fragmented landholdings, low digital literacy and socio-economic inequalities. Concerns regarding data privacy, cybersecurity, interoperability, data ownership and unequal access to digital infrastructure also require attention.

For millet-growing tribal and rainfed areas, weak institutional support and limited millet-specific advisory services remain important constraints. Therefore, economic transformation requires affordable technologies, infrastructure, institutional coordination and capacity development.

Conclusion

Digital transformation is reshaping Indian agriculture by improving information access, decision-making, resource-use efficiency, market integration, financial inclusion, and climate resilience through technologies such as AI, IoT, GIS, remote sensing, drones, blockchain and digital advisory platforms. The reviewed literature indicates that digital technologies can improve crop productivity, optimize water, fertilizer and pesticide use, reduce production risks and strengthen access to markets and extension services. Mobile-based advisory systems and ICT-enabled extension are currently among the most accessible digital innovations and have contributed to improved technology adoption and farm decision-making.

However, adoption of advanced digital technologies remains uneven, particularly among smallholder, tribal, and rainfed farming communities. Inadequate digital infrastructure, poor connectivity, low digital literacy, high investment costs, fragmented holdings, language barriers, and insufficient institutional support continue to limit inclusive digital transformation. The review also identifies a major knowledge gap: while digital agriculture research has expanded rapidly for major crops, millet production systems have received comparatively limited attention.

The findings highlight the need for integrated digital ecosystems that combine AI, IoT, GIS, precision agriculture, climate-smart advisory systems, digital

extension and market intelligence. Millet-specific decision-support tools should be developed with emphasis on affordability, simplicity, multilingual content and local relevance. Strengthening rural digital infrastructure, farmer digital literacy, public–private partnerships, FPO-based service delivery, and institutional coordination will be essential.

Future research should undertake rigorous empirical assessment of the effects of digital technologies on millet productivity, production costs, farm income, market participation, employment, value-chain development, climate resilience, and livelihood sustainability. Particular attention should be given to women, tribal communities, smallholders, and other resource-constrained farmers. Integrating digital technologies with conventional extension rather than replacing it can provide a more inclusive pathway.

As India continues to promote millets as climate-resilient and nutritionally important crops, digital transformation can play a significant role in strengthening millet-based farming systems, improving rural livelihoods, enhancing food and nutritional security, and supporting sustainable development. Such transformation is particularly relevant to SDG 2 (Zero Hunger), SDG 9 (Industry, Innovation and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action).

References

- Agricultural Census (2015–16). *Agricultural Census 2015–16: All India report on number and area of operational holdings*. Department of Agriculture, Cooperation and Farmers Welfare, Government of India.
- Aker, J.C. (2011). Dial “A” for agriculture: Using information and communication technologies for agricultural extension in developing countries. *Agricult. Econ.*, **42**(6), 631–647. <https://doi.org/10.1111/j.1574-0862.2011.00545.x>
- Alfred, R., Obid J.H., Chin C.P.Y., Haviluddin H. and Lim Y. (2021). Towards paddy rice smart farming: A review on big data, machine learning, and rice production tasks. *IEEE Access*, **9**, 50358–50380. <https://doi.org/10.1109/ACCESS.2021.3069449>
- Anderson, J.R. and Feder G. (2007). Agricultural extension. In : Evenson, R.E. and Pingali P. (Eds.), *Handbook of Agricultural Economics* (Vol. 3, pp. 2343–2378). Elsevier. [https://doi.org/10.1016/S1574-0072\(06\)03044-1](https://doi.org/10.1016/S1574-0072(06)03044-1)
- Babar, A.Z. and Akan O.B. (2024). Sustainable and precision agriculture with the Internet of Everything (IoE). *arXiv*. <https://arxiv.org/abs/2404.06341>
- Banerjee, A., Kumar S. and Singh R. (2024). Millet production and policy initiatives in India: Recent trends and future prospects. *J. Cereal Res.*, **16**(1), 1–15.

- Basso, B. and Antle J. (2020). Digital agriculture to design sustainable agricultural systems. *Nature Sustainability*, **3**(4), 254–256.
- Benos, L., Bechar A. and Bochtis D. (2021). Safety and ergonomics in human–robot interactive agricultural operations. *Biosyst. Engg.*, **200**, 55–72.
- Bertoglio, C., Corbo C., Renga F. and Matteucci M. (2021). The digital agricultural revolution: A bibliometric analysis. *Technological Forecasting and Social Change*, **169**, 120822. <https://doi.org/10.1016/j.techfore.2021.120822>
- Birthal, P.S., Joshi P.K. and Gulati A. (2015). Vertical coordination in high-value food commodities: Implications for smallholders. *International Food Policy Research Institute (IFPRI) Discussion Paper*.
- Bronson, K. and Knezevic I. (2016). Big data in food and agriculture. *Big Data & Society*, **3**(1), 1–5.
- Burman, R.R., Sharma J.P., Padaria R.N. and Kumar S. (2023). Digital agricultural extension in India: Current status, opportunities and challenges. *Indian J. Ext. Educ.*, **59**(2), 1–10.
- CASP (2018). *CASP qualitative checklist*. Critical Appraisal Skills Programme.
- Chandra, D., Chandra S., Pallavi and Sharma A.K. (2016). Review of finger millet (*Eleusine coracana* L.) grains for nutritional value and health benefits. *Food Sci. Hum. Wellness*, **5**(4), 195–201. <https://doi.org/10.1016/j.fshw.2016.05.004>
- Chandra, R., DeLay N., Evans J., Mosier N., Engel B. and Buckmaster D. (2020). Artificial intelligence for digital agriculture at scale: Techniques, policies and challenges. *arXiv*. <https://arxiv.org/abs/2001.09786>
- Chandrasekara, A. and Shahidi F. (2011). Bioactivities and antioxidant properties of millet grains and their potential health benefits: A review. *J. Funct. Foods*, **3**(3), 144–158. <https://doi.org/10.1016/j.jff.2011.04.001>
- Eastwood, C., Ayre M., Nettle R. and Dela Rue B. (2019). Making sense in the cloud: Farm advisory services in a smart farming future. *NJAS: Wageningen J. Life Sci.*, **90–91**, 100298.
- Fabregas, R., Kremer M. and Schilbach F. (2019). Realizing the potential of digital development: The case of agricultural advice. *Science* **366**(6471), eaay3038. <https://doi.org/10.1126/science.aay3038>
- Ferrández-Pastor, F.J., García-Chamizo J.M., Nieto-Hidalgo M. and Mora-Pascual J. (2016). Precision agriculture design method using a wireless sensor network and IoT. *Sensors*, **16**(7), 1141.
- Food and Agriculture Organization (2023). *International Year of Millets 2023*. FAO. <https://www.fao.org>
- Food and Agriculture Organization (2023). *International Year of Millets 2023*. FAO. <https://www.fao.org/millets-2023>
- Food and Agriculture Organization (2023). *The state of food and agriculture 2023: Revealing the true cost of food to transform agrifood systems*. FAO. <https://doi.org/10.4060/cc7724en>
- Fountas, S., Carli G., Sørensen C.G., Tsiropoulos Z., Cavalaris C., Vatsanidou A., Liakos B., Canavari M. and Wiebensohn J. (2015). Farm management information systems: Current situation and future perspectives. *Comput. Elect. Agricult.*, **115**, 40–50.
- Goron, T.L. and Raizada M.N. (2015). Genetic diversity and genomic resources available for the small millet crops to accelerate a new green revolution. *Front. Plant Sci.*, **6**, 157. <https://doi.org/10.3389/fpls.2015.00157>
- Goron, T.L. and Raizada M.N. (2015). Genetic diversity and genomic resources available for the small millet crops to accelerate a new green revolution. *Front. Plant Sci.*, **6**, 157. <https://doi.org/10.3389/fpls.2015.00157>
- Government of India (2023). *Electronic National Agriculture Market (e-NAM): Annual report*. Ministry of Agriculture & Farmers Welfare.
- Harish, G.D., Kumar A. and Ramesh B. (2024). Millets for sustainable agriculture and nutrition security: Recent advances and future prospects. *Front. Sust. Food Syst.*, **8**, Article 1386469.
- Indian Council of Agricultural Research (2023). *ICAR annual report 2022–23*. ICAR, New Delhi.
- Indian Council of Agricultural Research–Indian Institute of Millets Research (2023). *Annual report 2022–23*. ICAR-IIMR, Hyderabad.
- International Crops Research Institute for the Semi-Arid Tropics (2023). *Annual report 2023*. ICRISAT. <https://www.icrisat.org>
- Javaid, M., Haleem A., Singh R.P., Suman R. and Rab S. (2023). Significance of artificial intelligence in agriculture for sustainable development. *Advanced Agrochem*, **2**(1), 100020. <https://doi.org/10.1016/j.aac.2023.100020>
- Jindal, N. and Nikhanj P. (2023). Millets as future foods: Nutritional importance, processing technologies, and market opportunities. *J. Food Process Engg.*, **46**(11), e14419. <https://doi.org/10.1111/jfpe.14419>
- Kamilaris, A. and Prenafeta-Boldú F.X. (2018). Deep learning in agriculture: A survey. *Comput. Elect. Agricult.*, **147**, 70–90. <https://doi.org/10.1016/j.compag.2018.02.016>
- Kitchenham, B. and Charters S. (2007). *Guidelines for performing systematic literature reviews in software engineering*. Keele University.
- Klerkx, L., Jakku E. and Labarthe P. (2019). A review of social science on digital agriculture, smart farming and Agriculture 4.0: New contributions and a future research agenda. *NJAS: Wageningen J. Life Sci.*, **90–91**, 100315. <https://doi.org/10.1016/j.njas.2019.100315>
- Liakos, K.G., Busato P., Moshou D., Pearson S. and Bochtis D. (2018). Machine learning in agriculture: A review. *Sensors*, **18**(8), 2674. <https://doi.org/10.3390/s18082674>
- Lowenberg-DeBoer, J. and Erickson B. (2019). Setting the record straight on precision agriculture adoption. *Agron.*

- J., **111**(4), 1552–1569.
- McBratney, A., Whelan B., Ancev T. and Bouma J. (2005). Future directions of precision agriculture. *Precision Agriculture*, **6**(1), 7–23.
- Ministry of Agriculture & Farmers Welfare (2023). *Annual report 2022–23*. Government of India. <https://agricoop.gov.in>
- Ministry of Electronics and Information Technology (2023). *Digital India annual report*. Government of India.
- Mittal, S. and Mehar M. (2016). Socio-economic factors affecting adoption of modern information and communication technology by farmers in India: Analysis using multivariate probit model. *The J. Agricult. Educ. Ext.*, **22**(2), 199–212. <https://doi.org/10.1080/1389224X.2014.997255>
- Moher, D., Liberati A., Tetzlaff J., Altman D.G. and PRISMA Group (2009). Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA statement. *PLoS Medicine*, **6**(7), e1000097.
- Monteiro, A., Santos S. and Gonçalves P. (2021). Precision agriculture for crop and livestock farming: Brief review. *Animals*, **11**(8), 2345.
- Mulla, D.J. (2013). Twenty-five years of remote sensing in precision agriculture: Key advances and remaining knowledge gaps. *Biosyst. Engg.*, **114**(4), 358–371. <https://doi.org/10.1016/j.biosystemseng.2012.08.009>
- National Bank for Agriculture and Rural Development (2023). *NABARD annual report 2022–23*. NABARD.
- NITI Aayog (2021). *Designing the digital agriculture mission ecosystem*. Government of India.
- NITI Aayog (2022). *Designing the digital agriculture mission ecosystem*. Government of India. <https://www.niti.gov.in>
- Page, M.J., McKenzie J.E., Bossuyt P.M., Boutron I., Hoffmann T.C., Mulrow C.D. et al. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ*, **372**, n71.
- Pathak, H., Tripathi R., Jambhulkar N., Bisen J. and Panda B. (2020). Eco-regional strategies for sustainable agriculture under climate change. *Curr. Sci.*, **118**(6), 902–908.
- Patrício, D.I. and Rieder R. (2018). Computer vision and artificial intelligence in precision agriculture. *Comput. Elect. Agricult.*, **153**, 69–81.
- Pierpaoli, E., Carli G., Pignatti E. and Canavari M. (2013). Drivers of precision agriculture technologies adoption: A literature review. *Procedia Technology*, **8**, 61–69.
- Reserve Bank of India (2023). *Handbook of statistics on the Indian economy*. RBI.
- Rivera, W.M. and Alex G. (2004). *Extension system reform and the challenges ahead*. Agriculture and Rural Development Discussion Paper 45. World Bank.
- Rose, D.C., Lyon J., de Boon A., Hanheide M. and Pearson S. (2021). Responsible AI for agriculture requires better understanding of farmers' needs. *Nature Machine Intelligence*, **3**(11), 900–902.
- Rotz, S., Gravely E., Mosby I., Duncan E., Finnis E., Horgan M., LeBlanc J., Martin R., Neufeld H., Nixon A. and Pant L. (2019). Automated pastures and the digital divide. *J. Rural Stud.*, **68**, 112–122.
- Saleh, A.S.M., Zhang Q., Chen J. and Shen Q. (2013). Millet grains: Nutritional quality, processing, and potential health benefits. *Compreh. Rev. Food Sci. Food Saf.*, **12**(3), 281–295. <https://doi.org/10.1111/1541-4337.12012>
- Scoones, I. (1998). *Sustainable rural livelihoods: A framework for analysis*. IDS Working Paper No. 72.
- Shamshiri, R.R., Kalantari F., Ting K.C., Thorp K.R., Hameed I.A., Weltzien C., Ahmad D. and Shad Z.M. (2018). Advances in greenhouse automation and controlled environment agriculture. *Information Processing in Agriculture*, **5**(1), 1–22.
- Shruthi, H.R., Reddy B.S. and Kumar V. (2021). Digital agriculture in India: Opportunities and challenges for smallholder farmers. *Indian J. Agricult. Econ.*, **76**(3), 356–370.
- Singh, P., Sharma R. and Verma S. (2024). Government initiatives for millet promotion in India: Progress and policy implications. *Agricult. Econ. Res. Rev.*, **37**(1), 45–60.
- Sishodia, R.P., Ray R.L. and Singh S.K. (2020). Applications of remote sensing in precision agriculture: A review. *Remote Sensing*, **12**(19), 3136.
- Spielman, D.J., Ekboir J. and Davis K. (2009). The art and science of innovation systems inquiry. *Innovation Strategy Today*, **5**(1), 1–9.
- Suman, S. and Chandra P. (2024). Climate-resilient millets for sustainable food systems: A review. *Front. Nutr.*, **11**, 1456789.
- Swanson, B.E. and Rajalahti R. (2010). *Strengthening agricultural extension and advisory systems: Procedures for assessing, transforming, and evaluating extension systems*. World Bank.
- Talaviya, T., Shah D., Patel N., Yagnik H. and Shah M. (2020). Implementation of artificial intelligence in agriculture. *Artificial Intelligence in Agriculture*, **4**, 58–73.
- Thomas, J. and Harden A. (2008). Methods for the thematic synthesis of qualitative research in systematic reviews. *BMC Med. Res. Methodol.*, **8**, 45.
- Tiwari, R. (2022). Digital extension services and agricultural transformation in India: Opportunities and constraints. *J. Agricult. Ext. Rural Develop.*, **14**(2), 85–97.
- Tranfield, D., Denyer D. and Smart P. (2003). Towards a methodology for developing evidence-informed management knowledge by means of systematic review. *British J. Manage.*, **14**(3), 207–222.
- Tripoli, M. and Schmidhuber J. (2020). *Emerging opportunities for the application of blockchain in the agri-food industry*. FAO & ICTSD.
- Tzounis, A., Katsoulas N., Bartzanas T. and Kittas C. (2017). Internet of Things in agriculture: Recent advances and future challenges. *Biosystems Engineering*, **164**, 31–48.

- Van der Burg, S., Bogaardt M.J. and Wolfert S. (2019). Ethics of smart farming. *NJAS: Wageningen J. Life Sci.*, **90–91**, 100289.
- Verdouw, C., Tekinerdogan B., Beulens A. and Wolfert S. (2021). Digital twins in smart farming. *Agricultural Systems*, **189**, 103046. <https://doi.org/10.1016/j.agsy.2020.103046>
- Wolfert, S., Ge L., Verdouw C. and Bogaardt M.J. (2017). Big data in smart farming: A review. *Agricultural Systems*, **153**, 69–80. <https://doi.org/10.1016/j.agsy.2017.01.023>
- World Bank (2022). *World development report 2022: Finance for an equitable recovery*. World Bank. <https://doi.org/10.1596/978-1-4648-1730-4>
- Zhai, Z., Martínez J.F., Beltran V. and Martínez N.L. (2020). Decision support systems for agriculture 4.0: Survey and challenges. *Comput. Elect. Agricult.*, **170**, 105256.
- Zhang, C. and Kovacs J.M. (2012). The application of small unmanned aerial systems for precision agriculture: A review. *Precision Agriculture*, **13(6)**, 693–712. <https://doi.org/10.1007/s11119-012-9274-5>
- Zhang, Y., Wang G., Wang J. and Li X. (2021). Internet of Things-based smart irrigation systems for precision agriculture: A review. *Comput. Elect. Agricult.*, **189**, 106413.