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Digital extension and agro-advisory systems in India: Pathways to agricultural transformation

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Abstract

Agricultural extension systems in India are undergoing a profound transformation driven by digital technology and increasing farming complexity. Traditional extension services are currently constrained by high farmer-to-agent ratios, limited reach and delayed information delivery. In response, digital extension and agro-advisory systems have emerged as scalable mechanisms to enhance information access and decision support across value chains. This review synthesizes over 50 sources to evaluate the evolution and dynamics of these systems. This review adopts a semi-systematic narrative approach based on structured database screening and thematic synthesis. The analysis identifies a dual trajectory in India: policy-led digital public infrastructure such as Agri-Stack and Krishi Megh and market-driven Agri-tech innovation. While digital platforms have expanded advisory reach and timeliness, critical challenges regarding inclusiveness, data governance and advisory neutrality persist. Smallholder adoption remains limited by digital literacy and connectivity. Furthermore, the rise of private platforms that bundle advice with input sales raises concerns about objective recommendations. The paper argues that the next phase of agricultural transformation requires a hybrid "Phygital" extension model. This approach integrates advanced technologies such as artificial intelligence (AI), the Internet of Things (IoT) and remote sensing-with traditional institutions like Krishi Vigyan Kendras (KVKs) to ensure last-mile trust. This review concludes that digital extension, when designed inclusively and supported by transparent data-sharing protocols, can serve as a catalyst for productivity and resilience. However, targeted policy interventions are necessary to ensure benefits reach marginal farmers.

Keywords: Digital extension, agro-advisory systems, agricultural transformation, agri-tech, digital public infrastructure, India

Introduction

In India rural livelihoods revolve around agriculture which supports almost half the population with a decreasing contribution to the national gross domestic product. Regardless of significant improvements in crop performance, mechanization and input technologies, the industry is still confronted by long-standing problems associated with low productivity, climate uncertainty, market volatility and information asymmetry (World Bank, 2021; FAO, 2022) [22, 51]. Traditionally, agricultural extension services have been regarded as essential in terms of knowledge and innovations transfer to farmers, but, due to poor extension worker-farmer relations, scarcity of operational resources, slow information flow and low responsiveness to diverse and changing needs

of smallholders, the traditional system of extension services is becoming more and more restricted (Anderson and Feder, 2021; Meera *et al.*, 2021) [6, 35]. Globally, agricultural extension systems are undergoing rapid digital transformation, driven by increasing climate variability, market volatility and the need for real-time decision support. Recent studies highlight that digital advisory platforms are significantly improving access to timely and location-specific information, particularly in smallholder-dominated regions (Barrett *et al.*, 2020; Fabregas *et al.*, 2021) [8, 21]. The integration of mobile technologies, artificial intelligence and data-driven platforms has enabled a shift from linear extension models to interactive and demand-driven advisory ecosystems (Klerkx *et al.*, 2020; Birner *et al.*, 2021) [9, 28].

These structural limitations are presented with fresh opportunities provided by rapid development of digital technologies. The broad availability of mobile phones in the marketplace increased rural internet connectivity which increasing access to data-driven technologies (artificial intelligence, remote sensing, cloud computing and the Internet of Things) has facilitated the development of digital extension and agro-advisory systems (FAO, 2022; World Economic Forum, 2022) [22, 53]. These systems make it possible to access real-time, place-based and interactive advisory services, to make the process of agricultural knowledge dissemination dynamic, responsive to demands and based on the ecosystem instead of the linear view of agriculture as a process of supply. The COVID-19 pandemic also increased the use of digital advisory mechanisms, where their role in continuity of extension services cannot be ignored due to mobility and resource limitations (World Bank, 2021) [51]. The swift expansion of digital agriculture initiatives in India is enabled by solid policy interventions such as Digital Agriculture Mission, Agri-Stack, Krishi Megh and digitally enabled advisory platforms established by public-paid collaboration has been observed (Department of Agriculture and Farmers Welfare (DAFW), 2022; ICAR, 2021) [15, 16, 26]. Concurrently, there has been the development of the Agri-Tech startup ecosystem which provides integrated solutions that integrate digital advisory services with input delivery, mechanization as service, credit, insurance and market linkages (NASSCOM, 2023; IMARC Group, 2024) [24, 39]. Although these advancements are indicative of a paradigm shift in agricultural extension the issues of digital inclusion, data ownership, advisory legitimacy and sustainability in the long run are still present. In this context,

the given review critically evaluates the way in which digital extension and agro-advisory systems have been developed in India and how their market dynamics and institutional structures and how new advisory models have been designed, in addition to speculating on the technological paths in the future that will define the next stage of agricultural transformation. Nonetheless, whereas earlier studies (e.g. anderson and Feder, 2021; FAO, 2022) [6, 22] highlight the potential of technology that synthesize the benefits of integration between community digital infrastructure and agro-advisory models run by private actors in India is very low. Despite growing literature, there is limited integrative analysis linking digital public infrastructure, private agri-tech ecosystems and advisory delivery outcomes in India. This review addresses this gap through a multi-dimensional synthesis.

Objectives of the Review

1. To synthesize the evolution and typologies of digital extension and agro-advisory systems in India.
2. To evaluate their institutional, technological and market dynamics.
3. To identify gaps, governance challenges and future innovation trajectories.

Conceptual Framework

To understand the systemic integration of digital tools in Indian agriculture, this review utilizes a five-layer conceptual framework. This framework illustrates the flow from foundational digital public infrastructure to final socio-economic impacts.

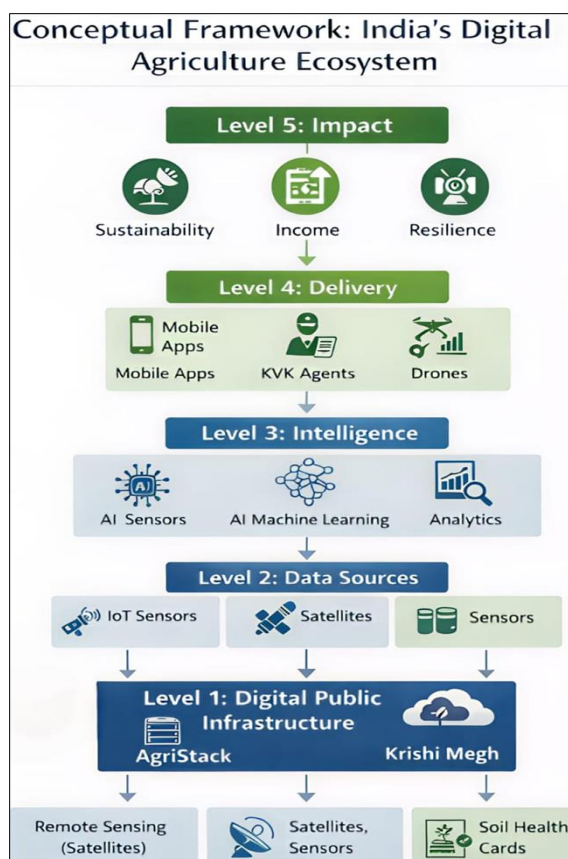


Fig 1: Conceptual Framework for India's Digital Agricultural Transformation

Review Methodology

This review adopts a semi-systematic narrative approach. Literature was identified using databases including Google Scholar, Scopus and Web of Science. Keywords included “digital extension,” “agro-advisory systems” and “ICT in agriculture.” The review included studies published between 2015 and 2025. Inclusion criteria comprised peer-reviewed articles, policy reports and empirical case studies related to digital agriculture and advisory systems. Studies lacking empirical or analytical rigor were excluded. Studies were screened based on relevance, empirical contribution and publication quality. Priority was given to peer-reviewed articles published after 2020, supplemented by policy reports and industry analyses to capture recent developments. The reviewed literature was categorized into five analytical themes:

1. Traditional vs digital extension models,
2. Institutional frameworks
3. Technology typology
4. Market and investment trends
5. Policy and governance challenges.

Only studies explicitly reporting empirical evidence or platform-level case studies were included, while conceptual commentaries without data support were excluded.

Traditional Agricultural Extension Services and their Limitations

The conventional agricultural extension services have in the past been the primary institutional process through which agricultural knowledge, technologies and innovations are transferred in research systems to the farmers. Extension delivery in India and other developing nations has majorly been based on the public-sector agency in whose interpersonal methods are included: farm visits, meetings, field demonstrations and training programmes. These strategies focus on the personal touch and practice and have been very instrumental in facilitating the use of better farming techniques. Traditional extension systems are however predominantly typified by top-down, supply-oriented flow of information and reliance on physical presence hence are less flexible and responsive to the dynamically changing agricultural situation (Anderson & Feder, 2007; Swanson & Rajalahti, 2010) [5, 47].

Despite their historical importance, traditional extension services face several persistent limitations. The low extensions-agents-farmer ratios and low institutional capacity hinder the capacity of extension personnel to deliver unending and personalized advisory services. The flow of information is commonly laggard and is one-way communication which is not effective in responding to time-based issues like pest infestations, weather disasters and stock market fluctuations. In addition, traditional methods of extension cannot cope with the lack of homogeneity in the farming systems, because generalized recommendations cannot reflect the differences in location-specific factors such as soil, climate and availability of resources. Such constraints have a major effect of diminishing the efficiency of the traditional extension to address the modern advisory demands of the small and marginal farmers (Anderson and Feder, 2007; Swanson and Rajalahti, 2010) [5, 47]. These limitations formed fruitful grounds to ICT-led changes that signifies the onset of digital extension models that transform advisory delivery into a networked and data-centric paradigm. Similar challenges have been documented across developing regions, where public extension systems struggle

with limited human resources, weak institutional capacity and low responsiveness to climate shocks (Davis *et al.*, 2020; Ragasa *et al.*, 2021) [14, 42]. Even in developed economies, traditional extension systems are increasingly being complemented by digital tools to enhance efficiency and scalability (Eastwood *et al.*, 2022) [20].

Digital Extension

The emergence of digital extension is primarily driven by the structural and operational constraints of traditional agricultural extension systems, including limited outreach, high transaction costs and delays in information dissemination. In this context, digital extension is increasingly viewed as a transformative approach that enhances the efficiency, scalability and inclusiveness of extension service delivery by enabling timely, data-driven and farmer-centric advisory support. According to Aker (2011) [3], digital extension can be understood as the application of mobile phones and related ICT tools to improve the delivery of agricultural information and services, thereby enhancing farmers' access to timely, relevant and actionable knowledge. Empirical evidence suggests that digital extension services improve farmers' access to information, reduce transaction costs and enhance decision-making efficiency, although impacts on productivity and income remain context-specific (Nakasone *et al.*, 2022; Cole & Fernando, 2021) [10, 38]. The effectiveness of such systems depends on complementary factors such as digital literacy, trust in information sources and institutional support (Steinke *et al.*, 2021; Aker *et al.*, 2020) [4, 46]. Similarly, Davis and Heemskerk (2012) [13] conceptualized digital extension as an ICT-enabled extension system that complements conventional approaches by improving outreach, interaction and effectiveness of agricultural advisory services.

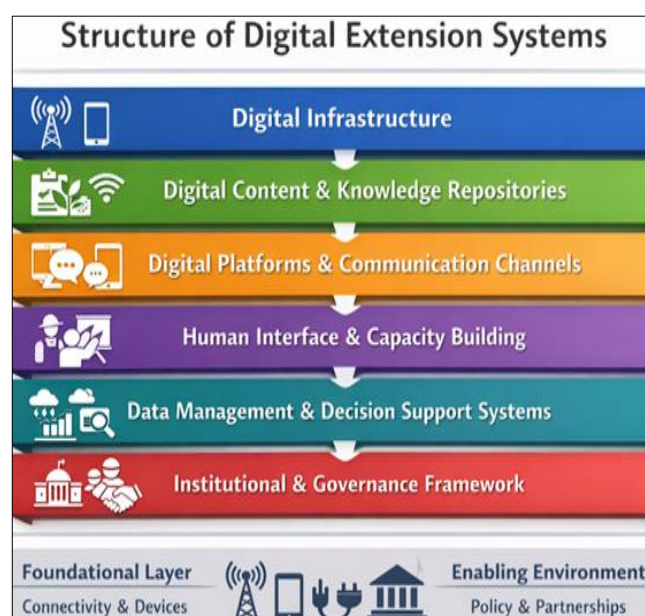


Fig 2: Structure of Digital Extension System

Advisory Services

Advisory services refer to organized efforts aimed at providing farmers and other agricultural stakeholders with technical guidance, information and decision-support to improve farm management, productivity and livelihoods. These services encompass recommendations related to crop

production, livestock management, plant protection, natural resource management, post-harvest handling and market participation. According to Davis (2008) ^[12], advisory services are defined as the systems through which farmers obtain knowledge, information and skills necessary to enhance agricultural performance and rural livelihoods.

Globally, advisory services are increasingly embedded within Agricultural Innovation Systems (AIS), where multiple actors-including governments, private firms and farmer organizations-co-produce knowledge and services (Klerkx *et al.*, 2020; Birner *et al.*, 2021) ^[9, 28].

Table 1: Timeline of Evolution of Digital Extension Advisory Services in India

Period	Phase of Evolution	Key Characteristics	Major Technologies
Pre-2000	Conventional Extension Phase	Face-to-face advisory services, group meetings, demonstrations, print and radio-based dissemination	Public extension system, mass media
2000-2010	Early ICT-enabled Extension	One-way information delivery; limited interactivity; focus on awareness creation	SMS alerts, helplines, agricultural web portals
2011-2015	ICT Expansion Phase	Improved reach and timeliness; basic two-way communication	Mobile phones, IVR systems, call centers, e-extension portals
2016-2019	Smartphone-based Digital Extension	Interactive, location-specific and real-time advisory services	Mobile apps, social media platforms, GPS-enabled advisories
2020-Present	Integrated & Intelligent Digital Extension	Data-driven, personalized and scalable advisory systems integrated with national digital infrastructure	AI-based decision support systems, cloud platforms, Agri-Stack, Krishi Megh, big data analytics

Market Status of Digital Technology/Agri-Tech

The global digital agriculture and agrifood technology (Agri-Tech) market has experienced rapid but uneven growth since 2020. Global agri-food-tech investment reached a historic peak in 2021 with funding exceeding USD 50 billion, driven by strong venture capital interest in precision agriculture, digital marketplaces, robotics and data-driven advisory systems. However, this surge was followed by a sharp correction, with global agri-food-tech investment declining to approximately USD 15.6 billion in 2023, reflecting broader macroeconomic tightening and a shift toward capital-efficient business models (Ag Funder, 2024) ^[1]. Despite this contraction in venture funding, the underlying market for digital agricultural technologies continues to expand. Enterprise adoption of satellite-based crop monitoring, AI-driven decision support systems and digital farm management platforms has increased substantially, particularly among agribusiness firms, insurers and governments seeking to manage climate risk and supply-chain volatility (Reuters, 2024) ^[43]. Market analysts estimate that the global digital agriculture market is projected to grow at a compound annual growth rate (CAGR) of 10-12 per cent through 2030, supported by increasing demand for precision farming, automation and climate-smart advisory solutions (Ag Funder, 2024) ^[1]. Recent global trends indicate a shift from rapid investment expansion toward more sustainable and impact-oriented Agri-Tech models, with increasing emphasis on climate resilience and data-driven agriculture (AgFunder, 2024; World Bank, 2022) ^[1, 52]. Studies suggest that long-term growth in digital agriculture will be driven more by institutional integration and data ecosystems than by standalone technological innovation (Trendov *et al.*, 2021; FAO, 2022) ^[22, 48]. India’s Agri-tech market reflects these global trends but is

shaped by the country’s smallholder-dominated agricultural structure and strong public-sector involvement. According to IMARC Group (2024) ^[24], the Indian Agri-tech market was valued at approximately USD 878 million in 2024 and is projected to reach USD 6.1 billion by 2033, growing at a CAGR of about 10.9 per cent. High-growth segments include AI-based agro-advisory services, satellite and drone analytics, mechanization-as-a-service (FaaS) and digital input-output marketplaces. Investment activity in India peaked in 2021 at around USD 1.3 billion, before declining to about USD 394 million in 2023, indicating a transition from rapid expansion to a more disciplined investment environment focused on profitability and scalable B2B models (Reuters, 2024) ^[43]. Looking ahead, future growth of the Indian Agri-tech market is expected to be driven by increasing smartphone penetration (exceeding 70% in rural households), government initiatives such as the Digital Agriculture Mission and Agri-Stack and rising demand for climate-resilient advisory systems (IMARC Group, 2024) ^[24]. Conservative forecasts suggest steady market expansion through the early 2030s, while upside scenarios enabled by digital public infrastructure, farmer producer organizations (FPOs) and embedded financial services could significantly accelerate adoption and investment, positioning India as one of the world’s fastest-growing digital agriculture markets (Inc42 Research, 2025) ^[25]. These market dynamics illustrate a shift from donor- or state-driven extension to hybrid techno-commercial ecosystems, prompting new governance frameworks that balance innovation with farmer equity. The recent ‘funding winter’ in the Indian Agri-Tech sector marked by a decline from USD 1.3 billion in 2021 to USD 394 million in 2023 should be viewed as a market maturation rather than a failure.

Table 2: Comparative Indicators of Global and Indian Agri-Tech Markets

Indicator	Global Agri-Tech Market	Indian Agri-Tech Market
Market Size (2024)	High growth with uneven distribution.	~USD 878 million.
Projected Size (2030-33)	Expanding at 10-12 per cent CAGR through 2030.	USD 6.1 Billion by 2033.
Top Technologies	Precision agriculture, robotics and supply-chain data.	AI-advisory, drone analytics and FaaS (Mechanization).
Key Policy Enablers	Climate risk mandates and enterprise ESG adoption.	Digital Agriculture Mission, Agri-Stack and FPO scaling.
Source: AgFunder (2024) ^[1] , IMARC (2024) ^[24] , Reuters (2024) ^[43]		

This correction signals a shift away from high-burn, customer-acquisition models toward 'capital-efficient' and 'outcome-based' B2B solutions. Future growth will likely be anchored in Digital Public Infrastructure (DPI) like Agri-

Stack, which reduces the cost of farmer acquisition for startups while providing the standardized data needed for high-precision, climate-resilient advisory services.

Table 3: Major Digital Extension / Agro-Advisory Platforms in India

S. No.	Platform/ Provider	Year of Launch/ Major Expansion	Functions
1.	Kisan Sarathi (Govt./ICAR)	2021	Connects farmers with ICAR scientists through a unified digital interface; provides crop, livestock and fisheries advisories in regional languages; enables two-way query-response mechanisms (Press Information Bureau (PIB), 2021; Indian Council of Agricultural Research (ICAR), 2021) ^[26, 40] .
2.	Krishi Megh (NARES Cloud, ICAR)	2020-2021	Provides national cloud infrastructure for agricultural research and extension; hosts digital advisory tools and datasets; supports virtual training and capacity building (ICAR, 2021) ^[26] .
3.	e-NAM (Advisory Modules)	2020-2022	Integrates real-time mandi prices with advisory dashboards; supports farmer decision-making on selling and storage; provides market intelligence alongside trading services (Department of Agriculture and Farmers Welfare [DAFW], 2022) ^[15, 16] .
4.	Kisan Drones Ecosystem	2022	Uses drones for crop monitoring and precision spraying advisories; supports training of drone pilots and Custom Hiring Centres; enables plot-level advisory services (PIB, 2022) ^[41] .
5.	Cropin (Cropin Cloud / Plot Intelligence)	2022	Uses AI and satellite imagery for crop health monitoring; provides yield prediction and climate-risk advisories; supports governments, FPOs and agribusinesses (Cropin, 2023) ^[11] .
6.	De-Haat	2020-2022	Provides AI-based crop advisories linked with input supply; integrates satellite data for localized recommendations; connects farmers to output markets (TechCrunch, 2021).
7.	Bharat Agri	2021-2023	Delivers AI-driven crop advisories via mobile applications; provides fertilizer and pesticide recommendations; operates subscription-based advisory services (Economic Times, 2022) ^[17] .
8.	EM3 Agri Services	2020-2023	Offers mechanization-as-a-service (FaaS); advises farmers on machinery selection and timing; uses digital scheduling platforms (EM3 Agri Services, 2023) ^[18] .
9.	Ninja cart (Advisory Integrations)	2021-2023	Provides advisory linked with fresh-produce procurement systems; supports quality standards and demand forecasting; integrates advisory with digital supply chains (Startup India, 2022).
10.	Ag-Next	2020-2022	Uses AI-based quality assessment for post-harvest advisory; supports grading and procurement decisions; serves agribusiness supply chains (Ag-Next, 2022) ^[2] .
11.	Fasal / FASAL-type Platforms	2020-2022	Provides micro-climate and weather-based crop advisories; supports irrigation and disease alerts; uses IoT and remote sensing technologies (Fasal, 2021) ^[23] .
12.	Krishi Hub / State Agri Portals	2020-2023	Disseminates government advisories digitally; uses SMS, mobile apps and portals in regional languages; acts as state-level digital extension gateways (State Government Agriculture Departments, 2022).
13.	SatSure / Satellite Advisory Services	2020-2023	Uses satellite imagery for crop and acreage monitoring; supports risk assessment and insurance advisory; provides large-scale agricultural analytics (Sat Sure Analytics, 2023) ^[45] .
14.	PM-Kisan Digital Integrations	2020-2023	Links farmer registry data with advisory dissemination; enables targeted messaging to beneficiaries; supports convergence with extension and welfare schemes (DAFW, 2022) ^[15, 16] .
15.	Smart Irrigation Advisory Systems	2020-2024	Uses IoT sensors for real-time soil-moisture monitoring; provides irrigation scheduling advisories; improves water- and energy-use efficiency (Ministry of Agriculture and Farmers Welfare, 2023) ^[36] .
16.	Soil Health Digital Card (SHC)	2020-2022	Digitizes soil testing data; provides nutrient and fertilizer advisories; supports national and state soil health programmes (ICAR, 2021) ^[26] .
17.	Market Intelligence Platforms	2020-2023	Provides price forecasting and demand analysis; supports marketing and storage decisions; integrates advisory with market dashboards (DAFW, 2022) ^[15, 16] .
18.	Climate Risk Advisory Platforms	2020-2023	Provides localized weather and climate alerts; supports crop contingency planning; assists in climate-risk mitigation strategies (Industry Reports, 2023).
19.	Livestock & Fisheries Advisory Platforms	2020-2023	Provides species-specific health and nutrition advisories; supports disease surveillance and vaccination alerts; tailored for allied agricultural sectors (Ministry of Fisheries, Animal Husbandry and Dairying, 2022) ^[37] .
20.	Vernacular Chatbot & IVR Systems	2020-2024	Provides voice-based advisories in local languages Enables two-way farmer interaction Widely used for low-literacy farmers (PIB, 2021; Industry Reports, 2023) ^[40] .

Comparative studies across countries reveal that successful digital advisory platforms integrate data analytics with localized knowledge systems, ensuring contextual relevance and farmer trust (Nakasone *et al.*, 2022; Van Etten *et al.*, 2021) ^[38, 49]. However, challenges related to interoperability, data governance and scalability persist globally.

Critical Assessment of Digital Agro-Advisory Platforms

While digital agro-advisory platforms have significantly

expanded the reach of extension services and their effectiveness varies across farmer categories. Public platforms emphasize inclusiveness and scale but often lack personalization whereas private platforms provide customized advisories but are concentrated among commercially viable farmers. Smallholder adoption remains constrained by digital literacy, connectivity and affordability. Furthermore, many platforms rely on bundled business models combining advisory with inputs or markets, raising

concerns about advisory neutrality. These challenges suggest that digital extension should complement, rather than replace, traditional extension systems. This indicates that digital extension alone cannot ensure equitable outcomes without institutional mediation and regulatory oversight.

Table 4: Structural Gaps and Performance Criteria in India's Digital Advisory Ecosystem

Evaluation Criteria	Public Platforms	Private Platforms	Common Gaps
Inclusiveness	High	Moderate	Gender bias
Personalization	Low	High	Cost barriers
Data governance	Limited	Proprietary	Trust deficit
Sustainability	Depends on funding	Profit-driven	Poor continuity

Despite rapid growth in digital platforms, current agro-advisory systems remain limited in their ability to deliver fully personalized, predictive and adaptive recommendations at scale. These limitations have prompted the emergence of advanced technologies such as artificial intelligence, IoT, remote sensing, blockchain and robotics, which are expected

to shape the next generation of agro-advisory systems. The contrasting design logic between public and private advisory platforms underscores the need for interoperability standards and transparent data-sharing protocols.

A significant emerging challenge in the private Agri-Tech ecosystem is the risk to 'advisory neutrality'. Many private platforms utilize bundled business models where technical advice is linked to the sale of inputs or procurement services. This creates a potential 'algorithmic bias,' where recommendations might prioritize a partner brand's products over more sustainable, low-cost alternatives. Ensuring the objectivity of digital advice requires a regulatory framework that enforces transparency in the logic of automated recommendations to protect farmers from commercially driven misinformation.

Emerging research highlights concerns regarding algorithmic bias, advisory neutrality and unequal access to digital services, particularly among marginalized farmer groups (Barrett *et al.*, 2020; Rotz *et al.*, 2021) [8, 44]. These issues necessitate robust governance frameworks to ensure transparency, inclusiveness and accountability in digital advisory ecosystems.

Table 5: Major Digital Agro-Advisory Platforms Across Countries

S. No.	Platform /Provider	Country	Year of Launch / Major Expansion	Functions
1	Climate FieldView (Bayer – Expansion Phase)	USA	2020-2024	Provides AI-driven farm analytics, yield prediction and precision advisory using satellite and big data platforms (Wolfert <i>et al.</i> , 2021; Eastwood <i>et al.</i> , 2022) [20].
2	Granular Insights (Corteva – Digital Expansion)	USA	2020-2023	Offers integrated farm management and decision-support systems combining financial, agronomic and operational advisory (Klerkx <i>et al.</i> , 2020; Birner <i>et al.</i> , 2021) [9, 28].
3	Prospera AI Platform (Expansion)	Israel	2020-2024	Uses computer vision and AI for real-time crop monitoring, pest detection and automated advisory recommendations (Liakos <i>et al.</i> , 2021; Zhang <i>et al.</i> , 2021) [33, 55].
4	Pinduoduo Smart Agriculture (Advanced Phase)	China	2020-2024	Integrates AI, cloud computing and digital marketplaces to provide advisory linked with supply chains and price intelligence (Zhang <i>et al.</i> , 2021; FAO, 2022) [22, 55].
5	Alibaba ET Agricultural Brain (Expansion)	China	2020-2023	AI-enabled decision-support system for crop and livestock management using big data analytics and predictive modeling (Trendov <i>et al.</i> , 2021; FAO, 2022) [22, 48].
6	Solinftec Digital Platform (Global Scaling)	Brazil	2020-2024	Provides IoT-based real-time monitoring, predictive analytics and automation advisory for large-scale farming systems (Rotz <i>et al.</i> , 2021; Wolfert <i>et al.</i> , 2021) [44].
7	Agrotools Analytics Platform (Expansion)	Brazil	2020-2023	Uses satellite-based crop intelligence, risk analytics and climate advisory tools for agribusiness decision-making (Eastwood <i>et al.</i> , 2022; Nakasone <i>et al.</i> , 2022) [20, 38].
8	Xarvio Digital Farming Solutions (BASF Expansion)	Germany	2020-2024	AI-driven crop protection advisory, disease prediction and input optimization tools for precision agriculture (Klerkx & Rose, 2023; Liakos <i>et al.</i> , 2021) [29, 33].
9	Akkerweb DSS Platform (Advanced Integration)	Netherlands	2020-2023	Decision-support system integrating soil, weather and crop data for climate-smart and sustainable advisory (Eastwood <i>et al.</i> , 2022; Klerkx <i>et al.</i> , 2020) [20, 28].
10	One Soil Platform (AI Expansion)	Europe (multi-country)	2020-2023	Provides satellite-based crop monitoring, field zoning and precision advisory using machine learning models (Wolfert <i>et al.</i> , 2021; Zhang <i>et al.</i> , 2021) [55].
11	FarmLogs (Data Platform Expansion)	USA	2020-2022	Offers farm-level data analytics, crop performance monitoring and decision-support advisory tools (Klerkx <i>et al.</i> , 2020; Nakasone <i>et al.</i> , 2022) [28, 38].
12	Taranis AI Platform (Scaling Phase)	Israel	2020-2024	High-resolution imagery and AI-based pest detection enabling ultra-precise advisory recommendations (Liakos <i>et al.</i> , 2021; Klerkx & Rose, 2023) [29, 33].
13	CropX Smart Farming Platform (IoT Expansion)	Israel / USA	2020-2024	IoT-based soil sensors providing irrigation, nutrient and climate advisory through real-time analytics (Wolfert <i>et al.</i> , 2021; FAO, 2022) [22].
14	Farmers Edge Digital Platform (Global Expansion)	Canada	2020-2023	Provides satellite imagery, weather analytics and predictive advisory for precision farming (Eastwood <i>et al.</i> , 2022; Nakasone <i>et al.</i> , 2022) [20, 38].
15	eFishery Platform (Smart Aquaculture Advisory)	Indonesia	2020-2024	Uses IoT and AI for feeding automation and aquaculture advisory systems improving productivity (FAO, 2022; Trendov <i>et al.</i> , 2021) [22, 48].

Table 5 demonstrates that global digital agro-advisory platforms are predominantly driven by artificial intelligence, big data analytics and IoT-enabled decision-support systems, with a strong focus on precision agriculture and large-scale farm management. In contrast, developing-country systems emphasize accessibility, scalability and smallholder inclusion.

Future Technologies for Agro-Advisory Systems

The next generation of agro-advisory systems is expected to be shaped by advanced technologies such as edge computing, federated learning and digital twins, enabling decentralized, adaptive and privacy-preserving decision support systems (Wolfert *et al.*, 2021; Klerkx & Rose, 2023) ^[29]. The post-2020 decade marks a convergence of digital public infrastructure and frontier technologies, redefining advisory ecosystems into intelligent, data-driven systems capable of predictive analytics and automation.

Artificial Intelligence (AI) and Generative AI

Artificial Intelligence (AI) refers to computational systems capable of learning from data, recognizing patterns and making predictions or recommendations with minimal human intervention. In agriculture, AI is increasingly combined with machine learning (ML), deep learning and more recently generative AI, which can produce human-like text, images and conversational responses for decision support (Liakos *et al.*, 2018; FAO, 2022) ^[22, 32].

AI is widely applied in pest and disease diagnostics through image recognition, yield prediction using historical and real-time data, crop stress detection and personalized advisory recommendations based on soil, weather and crop stage. Generative AI chatbots enhance agro-advisory systems by enabling conversational interfaces in local languages, allowing farmers to query recommendations, clarify doubts and receive context-specific guidance in real time (Kshetri, 2023; FAO, 2022) ^[22, 31]. AI also supports risk assessment for insurance and climate-smart decision-making. The AI in agriculture market is estimated at USD 1.7-2.0 billion in the early 2020s, with forecasts suggesting growth to USD 10-12 billion by 2030, reflecting compound annual growth rates (CAGR) exceeding 20 per cent (Markets and Markets, 2023; IMARC, 2024) ^[24, 34]. This rapid growth is attributed to declining computational costs, improved data availability and increasing adoption by agribusinesses and governments. AI is therefore expected to form the core intelligence layer of future agro-advisory systems (FAO, 2022) ^[22].

Internet of Things (IoT)

The Internet of Things (IoT) refers to interconnected networks of physical devices such as sensors, actuators and embedded systems that collect, transmit and process data in real time. In agriculture, IoT enables continuous monitoring of field and farm conditions (Wolfert *et al.*, 2017). IoT devices are used to monitor soil moisture, nutrient levels, temperature, humidity and micro-climatic variations. These real-time data streams feed agro-advisory platforms that generate irrigation scheduling advisories, nutrient recommendations and early warnings for stress or disease outbreaks. IoT-enabled advisory systems are particularly valuable in precision irrigation, protected cultivation and high-value crops, where timely interventions significantly

affect productivity and resource efficiency (Kamilaris *et al.*, 2017) ^[27]. The IoT in agriculture market was valued at approximately USD 11-13 billion globally by 2022 and is projected to reach USD 30-35 billion by 2030, growing at a CAGR of around 14-16 per cent (IMARC, 2024; Ayaz *et al.*, 2019) ^[7, 24]. Although adoption among smallholders is constrained by cost and maintenance issues, falling sensor prices and integration with advisory and irrigation platforms indicate strong long-term growth potential.

Remote Sensing and Digital Twins

Remote sensing involves the acquisition of information about crops and land surfaces using satellite or aerial sensors. Digital twins are virtual replicas of physical farming systems that simulate crop growth, soil processes and management scenarios using real-time and historical data (Verdouw *et al.*, 2021) ^[50]. High-resolution satellite imagery enables early detection of crop stress, pest infestation and nutrient deficiencies across large areas. When combined with crop models, these data support region-specific agro-advisories and risk alerts. Digital twins allow scenario simulation such as testing irrigation or fertilizer strategies virtually before implementation thereby reducing risk and improving decision quality. These technologies are increasingly adopted by governments, insurers and large agribusinesses for large-scale advisory and monitoring systems (Verdouw *et al.*, 2021; Cropin, 2023) ^[11, 50]. The agricultural remote sensing market is estimated at USD 2-3 billion globally, with projected growth to USD 8-10 billion by 2030, driven by demand for precision advisory and climate-risk monitoring (Markets and Markets, 2023) ^[34]. Digital twin applications in agriculture are still emerging but are expected to expand rapidly as computing power and data integration improve.

Blockchain and Data Platforms

Blockchain is a decentralized digital ledger technology that enables secure, transparent and tamper-proof recording of transactions and data. In agriculture, blockchain supports data governance, traceability and trusted information exchange across advisory ecosystems (Kshetri, 2018) ^[30]. Blockchain enhances agro-advisory systems by ensuring secure storage and sharing of farm data, soil records and advisory histories. It supports traceability in supply chains, improves trust in digital advisories and enables integration of advisory services with credit, insurance and certification systems. Although still at an early stage, blockchain-enabled data platforms are increasingly discussed in policy frameworks for digital agriculture and farmer data protection (World Bank, 2021; Kshetri, 2018) ^[30, 51]. The blockchain in agriculture and food market was valued at below USD 1 billion in the early 2020s, but forecasts suggest growth to USD 5-6 billion by 2030, with CAGRs exceeding 30 per cent in some estimates (Markets and Markets, 2023) ^[34]. Adoption in agro-advisory systems is expected to be gradual, driven by regulatory clarity and data-governance requirements.

Drones and Robotics

Agricultural drones and robotics refer to autonomous or semi-autonomous machines used for sensing, monitoring and performing farm operations. Drones primarily provide aerial data, while robots perform physical tasks such as spraying, weeding, or harvesting (Zhang & Kovacs, 2012) ^[54]. Drones

support agro-advisory systems by providing high-resolution imagery for crop health assessment, pest detection and nutrient stress analysis. Advisory platforms increasingly integrate drone data to generate plot-level recommendations. Robotics enables the execution of advisories-such as precision spraying or mechanical weeding reduces labour dependency. In countries like India, government-supported drone programmes are accelerating adoption for advisory and

precision input application (PIB, 2023; Zhang & Kovacs, 2012) [54].

The agricultural drone market is estimated at USD 4-5 billion globally and is projected to exceed USD 15 billion by 2030, growing at CAGRs above 20 per cent (Markets and Markets, 2023) [34]. Robotics in agriculture represents a longer-term growth segment, expected to expand rapidly as labour shortages and cost pressures increase.

Table 6: Emerging Technologies and their Advisory Roles

Technology	Core Function	Advisory Application	Adoption Barrier	Expected CAGR
Artificial Intelligence (AI)	Learning from data and recognizing patterns to make predictions.	Pest/disease diagnostics, yield prediction and personalized stage-specific advice.	High computational requirements and data availability.	>20%
Internet of Things (IoT)	Real-time collection and transmission of data via interconnected sensors.	Precision irrigation scheduling and early warnings for micro-climatic stress.	High initial cost and maintenance issues for smallholders.	14-16%
Remote Sensing (RS)	Acquiring land and crop information via satellite or aerial sensors.	Region-specific crop stress detection and large-scale acreage monitoring.	Need for high-resolution data and complex processing models.	~10-12% (Market expansion)
Blockchain	Decentralized and tamper-proof recording of data and transactions.	Secure storage of soil records and ensuring advisory neutrality/traceability.	Regulatory uncertainty and early stage of technological maturity.	>30%
Drones & Robotics	Autonomous machines for sensing, monitoring and farm operations.	Plot-level health assessment and precision application of inputs.	High equipment costs and labor skill requirements.	>20%

The Phygital Transition

To overcome the 'last-mile' trust deficit, India must adopt a 'Phygital' extension paradigm that leverages the reach of traditional institutions alongside frontier technologies. In this model, digital tools like AI-based diagnostics and satellite analytics act as 'force multipliers' for human extension workers rather than replacements. For instance, Generative AI chatbots can handle routine, vernacular queries on crop stages, allowing KVK agents to focus on complex, high-touch interventions such as community-level climate adaptation and field demonstrations. This synergy ensures that digital scale is anchored by institutional credibility. Digital agro-advisory systems play a critical role in advancing sustainable food systems by enabling resource-use efficiency, climate resilience and informed decision-making. However, their sustainability impacts remain uneven, as access disparities and data governance challenges may reinforce existing inequalities (Klerkx *et al.*, 2020; Barrett *et al.*, 2020) [8, 28]. Integrating digital advisory systems with agroecological practices and inclusive innovation frameworks is essential to ensure that technological advancements contribute to equitable and environmentally sustainable agricultural transformation (FAO, 2022; Birner *et al.*, 2021) [9, 22].

Conclusion

This review demonstrates that digital extension and agro-advisory systems are transitioning from proof-of-concept stages toward systemic integration within India’s agricultural ecosystem. Digital extension and agro-advisory systems have emerged as a transformative force in Indian agriculture, addressing long-standing limitations of traditional extension services related to reach, timeliness and personalization. This review highlights that while conventional extension played a pivotal role during earlier phases of agricultural development, its effectiveness has diminished in the face of

increasing climate variability, market volatility and the diverse information needs of smallholder farmers. Digital platforms leveraging mobile technologies, data analytics and cloud infrastructure have significantly expanded advisory outreach and enabled real-time, location-specific decision support, thereby complementing existing extension mechanisms rather than replacing them. Government-led initiatives such as the Digital Agriculture Mission, Agri-Stack, Krishi Megh, Kisan Sarathi and drone-based advisory programmes have laid a strong foundation for digital public infrastructure in agriculture. These initiatives have enhanced institutional convergence, improved data availability and fostered public-private partnerships in agro-advisory delivery. However, the review also reveals that public platforms often prioritize scale and inclusiveness, whereas private platforms focus on customized, value-added services, resulting in uneven access across farmer categories. Strengthening coordination between public extension systems (ICAR, state departments, KVKs) and private Agri-Tech platforms is therefore essential to ensure equitable and effective digital advisory dissemination.

Emerging technologies such as artificial intelligence, Internet of Things, remote sensing, digital twins, blockchain, drones and robotics are expected to shape the next generation of agro-advisory systems. Among these, AI-driven decision support and satellite-based analytics are likely to form the backbone of future advisory ecosystems by enabling predictive, adaptive and climate-resilient recommendations. Nevertheless, challenges related to data governance, advisory reliability, digital literacy and affordability persist. Without addressing these constraints, the benefits of advanced technologies may remain concentrated among resource-rich farmers and enterprises.

Policy Recommendations and Way Forward

1. Governance Integration: Digital agro-advisory

platforms should complement, not replace, public extension services. Institutional convergence among ICAR, State Departments of Agriculture, Krishi Vigyan Kendras and private Agri-Tech platforms is essential to ensure advisory credibility, last-mile trust and inclusiveness.

2. **Data Ethics and Infrastructure:** Initiatives such as Agri-Stack and Krishi Megh should prioritize interoperability, farmer consent and data privacy. Clear governance frameworks are required to enable ethical data sharing while supporting innovation in AI-driven advisory services.
3. **Inclusion and Capacity Building:** Targeted investments in digital literacy, vernacular interfaces, IVR systems and low-bandwidth solutions are necessary to ensure that small and marginal farmers benefit from digital advisory systems. Farmer Producer Organizations (FPOs) can act as critical intermediaries for collective adoption.
4. **Public-Private Accountability:** Public funding and procurement should increasingly focus on outcome-based models, linking advisory services to measurable improvements in productivity, sustainability and resilience. This can enhance accountability while supporting scalable private innovation.
5. **Research and Evaluation:** Rigorous impact evaluation of digital agro-advisory systems is needed to assess long-term effects on farmer income, climate adaptation and resource efficiency. Future research should also examine advisory neutrality, algorithmic bias and equity implications of advanced digital technologies.

Future Research Directions

Future research should employ mixed-method evaluations combining quantitative impact assessment (e.g., yield or income gains) with socio-technical analysis of platform governance and trust dynamics.

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