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Review

AI and geospatial innovations for Indian agriculture: Applications, policy support and emerging research frontiers

ABHISHEK DANODIA[1], SURESH KUMAR[1] and AJEET SINGH NAIN[2*]

[1]Indian Institute of Remote Sensing, Dehradun-248001(Uttarakhand) ,[2]Department of Agrometeorology, College of Agriculture, G. B. Pant University of Agriculture and Technology, Pantnagar-263145 (U.S. Nagar, Uttarakhand)
**Corresponding author's email id: nain_ajeet@hotmail.com*
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ABSTRACT: The recent advances in the Artificial Intelligence have accelerated the growth process and agriculture is no exception. A number of AI based applications are knocking the door and ready to take the world by storm. However, AI/ML applications in Agriculture will hardly be of any pragmatic use unless it is supported by spatial database. Geospatial technology is the best tool to capture large scale data set at varied spatio-temporal resolutions and lays the foundation for transforming modern agriculture by enabling precision farming, real-time monitoring and data-driven decision-making for sustainable resource management. This review presents an overview of recent advances in geospatial technologies and their applications in agriculture, with particular emphasis on the Indian context. The study discusses the role of remote sensing, Geographic Information Systems (GIS), unmanned aerial vehicles (UAVs), artificial intelligence (AI), machine learning (ML), cloud computing and geospatial analytics in agricultural monitoring and management. The integration of multi-source Earth Observation data from satellite missions such as Landsat, Sentinel, MODIS, Resources at, RISAT and emerging hyperspectral *and* thermal missions has significantly improved crop monitoring, yield prediction, digital soil mapping, disease and pest detection, soil moisture assessment and agricultural water management. AI and ML based approaches have enhanced the accuracy and efficiency of geospatial analyses, enabling predictive and automated agricultural applications. The review also highlights major challenges, including data quality, cloud contamination, limited ground truth observations, model interpretability and scalability for smallholder farming systems. Furthermore, ongoing government initiatives such as AgriStack, PMFBY, FASAL, CHAMAN and Krishi-DSS are discussed in the context of digital agriculture development in India. Future trends indicate a transition toward UAV based real-time farm monitoring, digital twins and climate-resilient predictive farming systems, supporting sustainable agricultural production, improved resource-use efficiency and enhanced food security.

Keywords: Artificial intelligence, Decision- making, Digital agriculture, Geospatial technology, Machine learning, UAV

Indian agriculture is undergoing a major transformation driven by technological advances, climate variability and increasing food-security demands. Agriculture employed about 46% of India's workforce in 2023-24, underscoring its importance for livelihoods and inclusive development (NITI Aayog, 2025). Traditional farming systems are therefore evolving toward precision and smart agriculture, where data-oriented decision-making can improve productivity, sustainability and resource-use efficiency. Smart agriculture integrates remote sensing (RS), Geographic Information Systems (GIS), smart sensing, wireless sensor networks (WSN), Global Navigation Satellite Systems (GNSS), Internet of Things (IoT), artificial intelligence (AI), machine learning (ML) and cloud computing for spatio-temporal monitoring and management of agricultural systems.

In the past decade, artificial intelligence (AI) and machine learning (ML) have increasingly emerged as important components of digital agriculture, supporting precision farming, intelligent crop monitoring, predictive analytics, disease detection, yield prediction, irrigation management and data-driven decision-making (Li *et al*., 2024; Wang *et al*., 2024). The integration of AI with remote sensing, Internet of Things (IoT) and other digital technologies is contributing to the transition from conventional experience-based management toward increasingly data-driven and automated agricultural systems (Li *et al*., 2024; Omia *et al*., 2023). At the same time, rapid developments in Earth Observation (EO) and remote sensing (RS) sensors at both global and national levels have expanded the availability

of multispectral, hyperspectral, thermal and microwave observations, substantially improving the capacity for spatially and temporally explicit agricultural monitoring and geospatial analysis (Omia *et al*., 2023; Li *et al*., 2024). International missions such as NASA's Landsat series, ESA's Sentinel missions, MODIS, SMAP and commercial high-resolution constellations provide datasets for crop monitoring, drought assessment, evapotranspiration estimation, disease and pest monitoring and precision agriculture. India has also developed an extensive EO capability through ISRO missions including Resourcesat, Cartosat, RISAT/EOS, Oceansat, INSAT, HySIS and NISAR. These missions provide complementary optical, thermal, hyperspectral and microwave observations for agricultural and environmental applications.

Geospatial innovation in agriculture can be defined as the integration of spatially referenced observations, geospatial databases, spatial analytics, modelling and decision-support technologies to characterize and manage agricultural systems across scales. The present landscape is moving from single-sensor and single-date analysis toward multi-source, time-series and AI-enabled workflows using satellite, UAV, IoT and field observations. Despite this progress, important gaps remain in transferability of AI models across regions and seasons, uncertainty quantification, availability of high-quality ground observations, interoperability of heterogeneous datasets, explainability, affordability and scalability for small and fragmented farms. This review addresses these gaps by synthesizing the status of geospatial technologies and AI/ML applications in Indian agriculture, examining major applications and Government of India programmes and identifying methodological, operational and research priorities for the next generation of agricultural geospatial systems.

REVIEW METHODOLOGY

This article follows a narrative review framework rather than a formal systematic-review protocol. Literature was selected through targeted searches of peer-reviewed scientific literature and authoritative technical/policy sources using combinations of terms such as "geospatial technology", "remote sensing", "GIS", "UAV", "artificial intelligence", "machine learning", "digital agriculture", "crop monitoring", "yield prediction", "soil mapping", "disease detection", "evapotranspiration" and "India". Priority was given to studies published during approximately 2015-2026 that demonstrated agricultural applications, validation or operational relevance in India, while seminal publications were retained for established vegetation/water indices and foundational methods. Official mission documentation from ISRO, NASA, ESA and Government of India programmes was also consulted for satellite specifications and policy/programme status. The selected literature was synthesized thematically under geospatial technologies, data analytics, agricultural applications, challenges, government programmes and future research directions.

Geospatial Technologies in Agriculture

Remote Sensing (RS)

RS plays a key role in modern agriculture by providing timely and non-destructive information about crop growth, health and stress conditions. Crops interact differently with electromagnetic radiation across the visible (VIS), near infrared (NIR)and shortwave infrared (SWIR) regions, producing unique spectral signatures on reflectance scale (Fig. 1). Healthy vegetation absorbs more red light due to chlorophyll activity and highly reflects

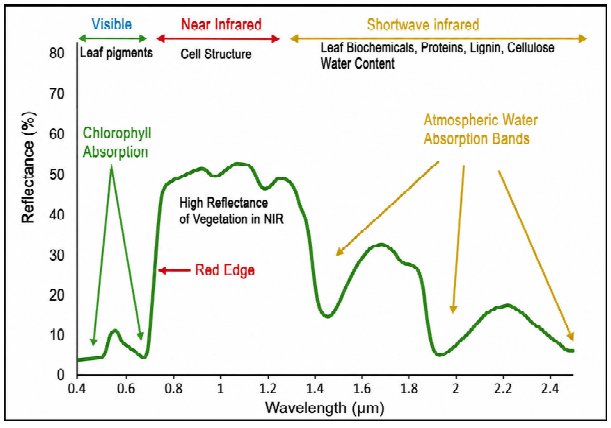


Fig.1: Schematic diagram of spectral signature of vegetation (Source: Roman and Ursu, 2016)

NIR radiation because of internal leaf structure of cells and tissues. In contrast, stressed or unhealthy crops exhibit reduced NIR reflectance and increased red reflectance. This spectral behaviour forms the basis for crop condition assessment using satellite/ airborne data.

Numerous Earth Observation (EO) and meteorological satellites were launched in last few decades by ISRO and other space agencies, which primarily works for natural resource management (NRM). The details of few Indian and foreign satellite sensors which are extensively utilized in the scientific study are enlisted in Table 1. Besides, a number of prestigious missions from different space agencies are expected to launch in recent future. The upcoming mission details are enlisted in Table 2. These enormous datasets are utilized in formation of different spectral vegetation indices which are further inculcate in various analytical and modelling exercise.

Spectral vegetation indices derived from remote sensing or airborne data are widely used for crop and soil condition assessment and monitoring in precision agriculture. Normalized Difference Vegetation Index (NDVI) is commonly used for evaluating crop vigour, biomass and vegetation dynamics, while Enhanced Vegetation Index (EVI) improves monitoring in dense canopies by reducing atmospheric effects. Soil Adjusted Vegetation Index (SAVI) minimizes soil background influence and is suitable for sparsely vegetated areas. Green Normalized Difference Vegetation Index (GNDVI) is effective for assessing chlorophyll content and nitrogen status, whereas Normalized Difference Water Index (NDWI) helps monitor crop water content and drought stress. Additionally, LAI-based indices support biomass and growth modelling through canopy structural analysis and red-edge indices enable early detection of crop stress and nutrient deficiencies. A few of the spectral indices with formula and their major applications are enlisted in Table 3.

Geographic Information Systems (GIS)

GIS has become an important geospatial tool for agricultural planning, monitoring and management by integrating spatial and non-spatial datasets related to crops, soil, water, climate and terrain in development of decision support system (DSS). GIS enables efficient collection, storage, analysis and visualization of agricultural information obtained from remote sensing satellites, GPS surveys, UAVs and field observations. In modern agriculture, GIS supports precision farming by providing location-specific information for crop management and resource optimization.

GIS functionality in agriculture includes spatial database creation, thematic mapping, overlay analysis, spatial querying, interpolation and temporal monitoring of agricultural parameters (Fig. 2). Multiple agricultural layers such as soil type, land use/land cover, crop acreage, irrigation networks, rainfall distribution, groundwater availability and fertilizer application zones can be integrated within a GIS environment to analyze spatial variability and support farm-level decision-making. GIS-based analysis helps in identifying suitable areas for crop cultivation, monitoring crop growth conditions and assessing drought- or flood-affected regions.

The integration of GIS and RS with advanced technologies has significantly improved generation

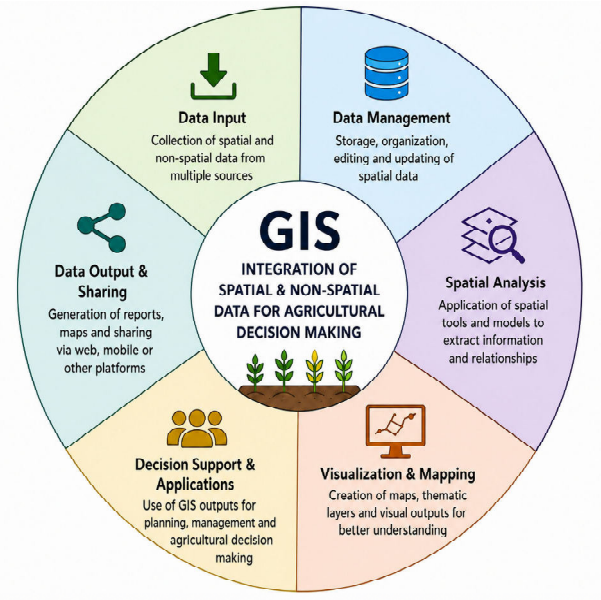


Fig. 2: GIS functionality in agricultural applications

Table 1: Details of satellite and sensors with their characteristics

S.N.	Satellite / Mission	Sensor	Year of Launch	Spatial Resolution (m)	Temporal Resolution / Revisit	Spectral Coverage / Characteristics
1	NISAR	L-band *and* S-band SAR	2025	3-10 (mode dependent)	12 days	Dual-frequency SAR (L-band: 1.25 GHz and S-band: 3.2 GHz); full polarimetric capability
2	Resourcesat-1/ 2/ 2A	LISS-IV	2003/ 2011/ 2016	5.8	5 days	3 bands: Green (0.52-0.59 µm), Red (0.62-0.68 µm), NIR (0.77-0.86 µm)
3	Resourcesat-1/ 2/ 2A	LISS-III	2003/ 2011/ 2016	23.5	24 days	4 bands: Green, Red, NIR, SWIR (1.55-1.70 µm)
4	Resourcesat-1/ 2/ 2A	AWiFS	2003/ 2011/ 2016	56	5 days	4 bands: Green, Red, NIR, SWIR
5	RISAT-1	SAR	2012	1–50 (mode dependent)	25 days	C-band SAR (5.35 GHz); multiple polarisation modes
6	RISAT- 2B	SAR	2019	0.3–1 (very-high-resolution modes)	Frequent spot-imaging opportunities	X-band SAR; day/night and all-weather imaging; agriculture and disaster-management applications
7	Oceansat-1/ 2/ 3	OCM	1999/ 2009/ 2022	360	2 days	Ocean Colour Monitor; VNIR observations
8	Cartosat-1/ 2/ 3	PAN Camera	2005/ 2007/ 2019	0.28-2.5	1-5 days	Panchromatic imagery
9	HySIS	Hyperspectral Imager	2018	30	5 days	60 VNIR (0.4-0.95 µm) and 256 SWIR bands (0.85-2.4 µm)
10	INSAT-3D/ 3DR/ 3DS	Imager *and* Sounder	2013/ 2016/ 2024	1-8 km	30 min	VIS, SWIR, MIR, TIR channels
11	Sentinel-1 A/B/C/D	C-SAR	2014/ 2016/ 2024/ 2025	5–40	6-12 days	C-band SAR dual polarization
12	Sentinel-2 A/B/C	MSI	2015/ 2017/ 2024	10, 20, 60	5 days	13 spectral bands from VIS to SWIR
13	Sentinel-3 A/B/C	OLCI / SLSTR	2016/ 2018/ 2026*	300-1000	1-2 days	Ocean, land surface temperature and color bands
14	Landsat- 8	OLI *and* TIRS	2013	15, 30, 100	16 days	11 bands: Coastal to Thermal IR
15	Landsat- 9	OLI-2 *and* TIRS-2	2021	15, 30, 100	16 days	VIS, NIR, SWIR, Thermal bands
16	MODIS	MODIS Terra/ Aqua	1999/ 2002	250-1000	1-2 days	36 bands from VIS to Thermal IR
17	SMAP	Radiometer / Radar	2015	9-36 km	2-3 days	L-band soil moisture observations
18	PlanetScope	Dove Sensors	2016 onward	3	Daily	RGB + NIR
19	WorldView-3	WV-3 Sensor Suite	2014	0.31-3.7	<1 day	Panchromatic, multispectral, SWIR, CAVIS
20	TerraSAR-X	X-band SAR	2007	1-16	11 days	X-band SAR imaging
21	Radarsat-2	SAR	2007	3-100	24 days	C-band SAR multi-polarization
22	EOS-04 (RISAT-1A)	C-band SAR	2022	3-50 (mode dependent)	~14–24 days; mode/coverage dependent	All-weather, day/night C-band SAR; multiple imaging modes for agricultural and environmental applications
23	EnMAP	Hyperspectral Imager	2022	30	27 days; ~4 days with off-nadir pointing	VNIR–SWIR hyperspectral imaging (420–2450 nm); 30 m spatial resolution

Table 2: Details of future satellite mission and their use in agriculture

Mission	Agency	Expected Capability	Relevance to Agriculture
TRISHNA	ISRO *and* Centre National d'Études Spatiales (CNES, France)	High-resolution thermal infrared observations	Crop water stress, evapotranspiration, irrigation management
Landsat Next	National Aeronautics and Space Administration	Enhanced spectral and temporal resolution	Advanced crop monitoring and land management
Sentinel Expansion Missions	European Space Agency	Thermal, hyperspectral, CO_2 monitoring	Precision agriculture and climate studies

Table 3: Commonly used spectral vegetation indices, formula and their major applications

Vegetation Index	Formula / Basis	Major Application
NDVI	(NIR − Red) / (NIR + Red)	Crop vigour, biomass, vegetation monitoring
EVI	G * ((NIR - RED) / (NIR + C1 * RED - C2 * BLUE + L))	Dense vegetation and precision agriculture
SAVI	((NIR - Red) / (NIR + Red + L)) * (1 + L) NIR	Sparse vegetation and exposed soil conditions
GNDVI	(NIR − Green) / (NIR + Green)	Chlorophyll and nitrogen assessment
NDWI	(NIR − SWIR) / (NIR + SWIR)	Crop water content and drought monitoring

of information necessitated for agricultural management and precision agriculture practices. Time-series satellite data processed within GIS platforms enabled long-term assessment along near real-time monitoring of crop health, vegetation stress, evapotranspiration and drought conditions. Modern geospatial and cloud platforms/ software are increasingly being used for large-scale agricultural data analysis and development of DSS. Thus, GIS and geospatial analysis have become integral components of smart and climate-resilient agriculture for improving productivity, sustainability and efficient natural resource management.

UAV / Drone-based sensing

Unmanned Aerial Vehicles (UAVs) is commonly known as drones, have emerged as an important platform for high-resolution geospatial data collection in agriculture as well as other natural resource management. UAV-based sensing provides ultra-high spatial resolution, flexible temporal observations and rapid data acquisition for monitoring crop conditions, plant health, irrigation status, soil variability and pest or disease outbreaks. Compared to satellite remote sensing, drones provide field-scale observations with greater operational flexibility and near real-time monitoring capability, making them highly suitable for precision agriculture applications.

Different types of drones are being used in geospatial data collection depending on the area coverage, flight duration and operational requirements. Multirotor drones (quadcopters and hexacopters) are widely used for agricultural surveys due to their vertical take-off capability, stable hovering and suitability for small and fragmented fields. Fixed-wing drones are preferred for large-area mapping because of their longer flight endurance and higher area coverage. Hybrid VTOL (Vertical Take-Off and Landing) drones combine the advantages of both multirotor and fixed-wing systems for efficient agricultural mapping.

UAVs are equipped with different sensors such as red-green-blue (RGB) cameras, multispectral sensors, hyperspectral sensors, thermal cameras and LiDAR systems for collecting high-resolution spatial data. The acquired data are generally stored in raster formats including GeoTIFF, JPEG, orthomosaics, digital surface models (DSM)and point cloud datasets. UAV-derived geospatial products are processed using photogrammetric and GIS software to generate vegetation indices, canopy height models, crop stress maps and 3D terrain information. A commonly used UAV platforms are solicited in

Table 4: Commonly used UAV platforms in geospatial applications

S.N.	UAV Platform	UAV Type	Major Features
1	DJI Phantom Series	Multirotor	High-resolution RGB imaging, easy operation, stable hovering
2	DJI Mavic Series		Compact and portable, high-quality imaging sensors
3	DJI Matrice Series		Advanced payload support, multispectral and thermal compatibility
4	Parrot Anafi		Lightweight UAV with RGB and thermal imaging support
5	Skydio Skydio X2		AI-enabled autonomous navigation and imaging
6	Sensefly eBee	Fixed-wing	Long flight endurance, large-area coverage
7	AgEagle RX-60		Long-duration flights with multispectral imaging capability
8	Delair UX11		High-accuracy photogrammetry and mapping
9	Quantum Systems Trinity	Hybrid VTOL	Combines vertical take-off with fixed-wing endurance
10	Yuneec H520	Hexacopter	Stable flight with interchangeable payloads

Table 5: AI/ML techniques and their agricultural applications

AI/ML Technique	Major Function	Agricultural Applications	Advantages	References
Random Forest (RF)	Classification *and* regression	Crop mapping, yield prediction, soil classification	High accuracy, handles large datasets efficiently	Nihar *et al*. (2022); Kalambukattu *et al*. (2025); Sukirti *et al*. (2023)
Support Vector Machine (SVM)	Supervised classification	Crop discrimination, disease detection	Effective with limited training data	Nihar *et al*. (2022); Singh *et al*. (2020); Kalambukattu *et al*. (2025)
Artificial Neural Network (ANN)	Pattern recognition	Yield forecasting, evapotranspiration estimation	Captures nonlinear relationships	Kalambukattu *et al*. (2018); Satpathi *et al*. (2024b)
Convolutional Neural Network (CNN)	Image feature extraction	Crop disease detection, UAV image analysis	High performance in image classification	Antony Ravi *et al*. (2026)
Decision Tree (DT)	Rule-based classification	Soil suitability analysis, crop classification	Easy interpretation and implementation	Singh *et al*. (2020); Sukirti *et al*. (2023)
Deep Learning Models	Automated feature learning	Precision agriculture, stress detection	High automation and improved prediction accuracy	Antony Ravi *et al*. (2026)
AI *and* GIS Integration	Spatial decision support	Precision farming and resource management	Real-time monitoring and spatial intelligence	Danodia *et al*. (2025); Satpathi *et al*. (2024b); Tiwari *et al*. (2025)

Table 4.

Advances in Geospatial Data Analytics

Advances in geospatial data analytics have significantly transformed modern agriculture through the integration of RS, GIS, artificial intelligence (AI), machine learning (ML), deep learning (DL), cloud computing and big data analytics. The rapid availability of multispectral geospatial datasets from satellites, UAVs, IoT sensors and field observations has created new opportunities for real-time agricultural monitoring and precision farming. AI and ML techniques are increasingly being used to analyze large geospatial datasets for crop classification, yield prediction, soil mapping, irrigation scheduling, pest detection and climate impact assessment. These techniques improve the speed, accuracy and automation of agricultural monitoring and assessment.

Various machine learning algorithms are widely used for crop classification, digital soil mapping, resource

assessment and yield estimation. Deep learning approaches have shown remarkable performance in extracting complex spatial and temporal patterns from satellite and UAV imagery. AI-driven geospatial analytics enable automated feature extraction, image segmentation, object detection and predictive modelling for smart agriculture applications. Cloud-based geospatial platforms are facilitating large-scale agricultural data processing and operational monitoring through DSS, webpage development, advisory services etc. The different AI/ML techniques, along with their utilization and applications across various themes, are illustrated in Table 5.

AI and ML methods are increasingly used to analyse large geospatial datasets for crop classification, yield prediction, digital soil mapping, irrigation scheduling, pest and disease detection and climate-impact assessment. Recent Indian applications include multi-temporal deep-learning crop classification (Antony Ravi *et al* , 2026), geospatial yield modelling for rabi pulses (Danodia *et al.*, 2025), rice yield prediction using SAR and optical data (Sah *et al.*, 2024) and machine-learning-based disease detection (Nainwal *et al.*, 2025). Their reported performance demonstrates the potential of AI/ML, but model quality is not determined by the algorithm alone. Independent spatial and temporal validation, representative training samples, class balance, uncertainty quantification and assessment of transferability across crops, seasons and agro-ecological regions are essential. Large training datasets can improve deep-learning performance but increase annotation effort, storage and computational cost; therefore, model selection should consider accuracy together with data requirements, interpretability, processing time and deployment constraints.

Major Applications

***Crop Types Classification*:** Crop types classification is a major application of geospatial technology in agriculture, where satellites and UAV imageries are exclusively used to identify and map different crops. Multispectral datasets from Sentinel and Landsat are commonly integrated with machine learning algorithms such as Random Forest and Support Vector Machine for crop discrimination (Nihar *et al*., 2022; Singh *et al*., 2020). Nihar *et al*. (2022) demonstrated the usefulness of multi-temporal Sentinel-2 data for sugarcane mapping at crop type scale at the field level. Using SVM and Random Forest classifiers, the study achieved high accuracies (kappa coefficient; 0.95 and 0.81, respectively), with cropping area estimates closely matching mill records (Fig. 3). Time-series vegetation indices help capture crop phenology and seasonal variability

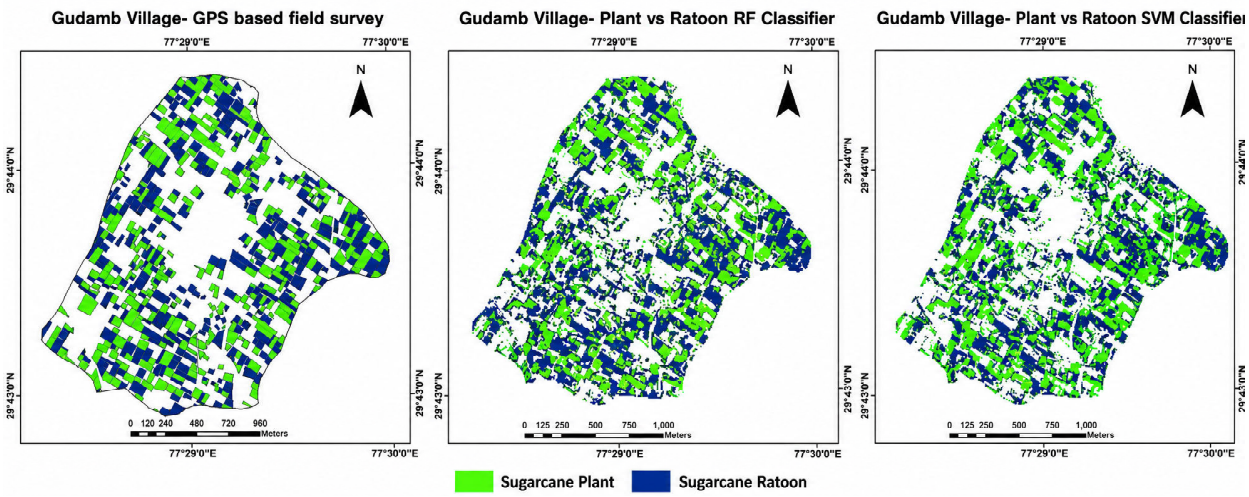


Fig. 3: Comparison of Plant and Ratoon Crop Classification with GPS Survey Data in Gudamb Village, KSCM Catchment (Source: Nihar *et al*., 2022)

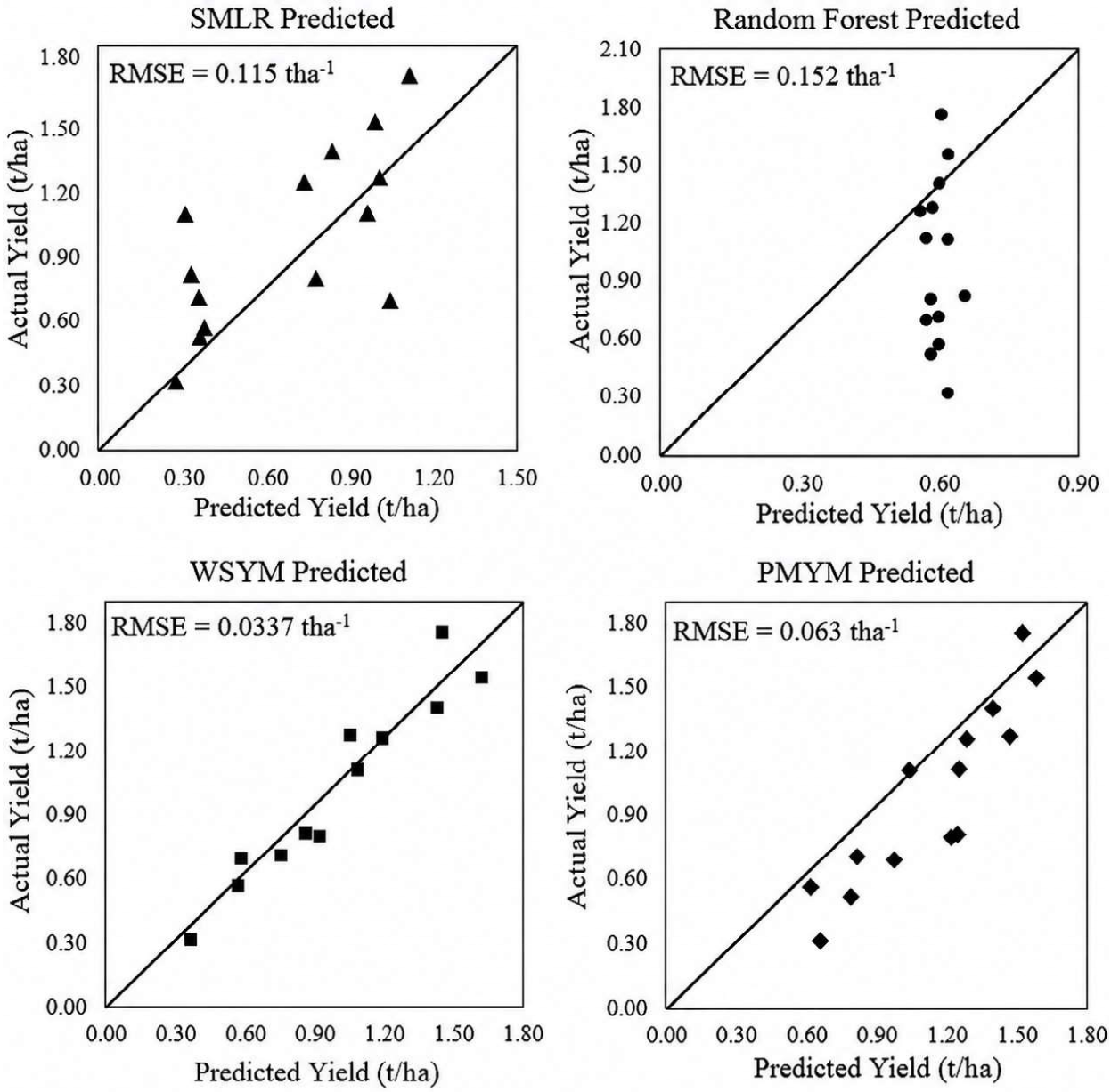


Fig. 4: Performance Comparison of Various Models for Field Pea Yield Prediction (Source: Danodia *et al*., 2025)

(Singh *et al*., 2022). Accurate crop maps support acreage estimation, crop inventory generation and agricultural policy planning. Deep learning techniques have further improved classification accuracy in heterogeneous agricultural landscapes (Antony Ravi *et al*., 2026).

***Crop Yield Prediction*:** Crop yield prediction using geospatial analytics integrates remote sensing data, weather information, soil parameters and crop growth indicators for forecasting agricultural production (Danodia *et al*., 2025; Pandey *et al*., 2023, Nain and Singh, 2016, Ranjan *et al*., 2012). Vegetation indices such as NDVI and EVI derived from satellite data are commonly used as predictors in machine learning and deep learning models (Sah *et al*., 2024). Danodia *et al*. (2025) developed and validated four yield prediction models for gram and field pea, including weather-based, machine learning, regression and phenology-based

approaches (Fig. 4). The Weighted Statistical Yield Model outperformed the others, achieving the lowest prediction errors with RMSE values of 0.040 t ha{ ¹ for gram and 0.037 t ha{ ¹ for field pea. Accurate yield forecasting supports food security planning, crop insurance and market management. Cloud-based geospatial platforms enable near real-time yield estimation over large agricultural regions.

***Disease and Pest Detection*:** Remote sensing and AI-based image analytics are increasingly used for disease and pest detection in crops. Multispectral, hyperspectral and thermal observations can capture physiological or spectral changes associated with biotic stress and several controlled and field studies have demonstrated detection before or around the onset of visible symptoms; however, the lead time is highly dependent on crop, pathogen, sensor, environment and validation design. Deep learning models such as Convolutional Neural Networks (CNNs) are widely used for automated disease recognition from UAV and field images (Nainwal *et al*., 2025). Early, validated detection can create an opportunity for timely and targeted intervention, but claims of reduced pesticide use should be made only where field management trials demonstrate such outcomes. Geospatial disease surveillance can also identify spatial hotspots of pest infestation and disease spread (Tiwari *et al*., 2025).

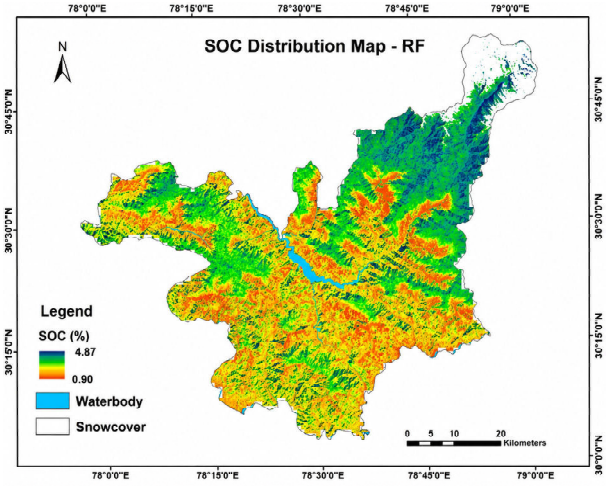


Fig. 5: Spatio-temporal map of SOC predicted by RF model in the study area (Source: Kalambukattu *et al*., 2025)

***Digital Soil Mapping*:** Digital Soil Mapping (DSM) uses RS, GIS, terrain parameters and machine learning approaches to predict spatial variability of soil properties (Kalambukattu *et al*., 2018). Geospatial datasets such as DEMs, multispectral imagery and climatic information are integrated for mapping soil texture, organic carbon, pH, salinity and nutrient status (Kalambukattu *et al*., 2025, Shashikumar *et al*., 2023). Kalambukattu *et al*. (2025) mapped soil organic carbon (SOC) at 30 m resolution using 421 georeferenced soil samples in the Indian Himalayan region, environmental covariates and machine learning models (RF, SVR and XGB). The Random Forest model performed best (R^2_{train} = 0.92; R^2_{test} = 0.72), revealing higher SOC concentrations in the northern regions and evergreen forests (2.88%) compared to other land-use types (Fig. 5). Algorithms such as Random Forest, ANN and regression kriging are widely applied for soil prediction also (Kalambukattu *et al*., 2018). DSM provides faster, cost-effective and spatially continuous soil information compared to conventional soil surveys. These maps are highly useful for precision nutrient management and land suitability analysis.

***Soil Health and Moisture Estimation*:** Geospatial technologies are extensively used for monitoring soil moisture and soil health parameters across agricultural landscapes. Microwave remote sensing missions such as SMAP and SAR-based observations provide reliable information on surface soil moisture under varying weather conditions. Spectral indices, thermal imagery and AI-based models are used for estimating soil organic matter, salinity and nutrient variability. Soil moisture maps are important for drought assessment, irrigation scheduling and climate-resilient agriculture. UAV thermal sensing has further improved field-scale moisture estimation accuracy.

***Agricultural Water Management*:** Geospatial technologies play an important role in agricultural water management through irrigation monitoring, evapotranspiration (ET) estimation and drought assessment. Satellite missions such as Landsat, MODIS and Sentinel-2 are widely used to estimate

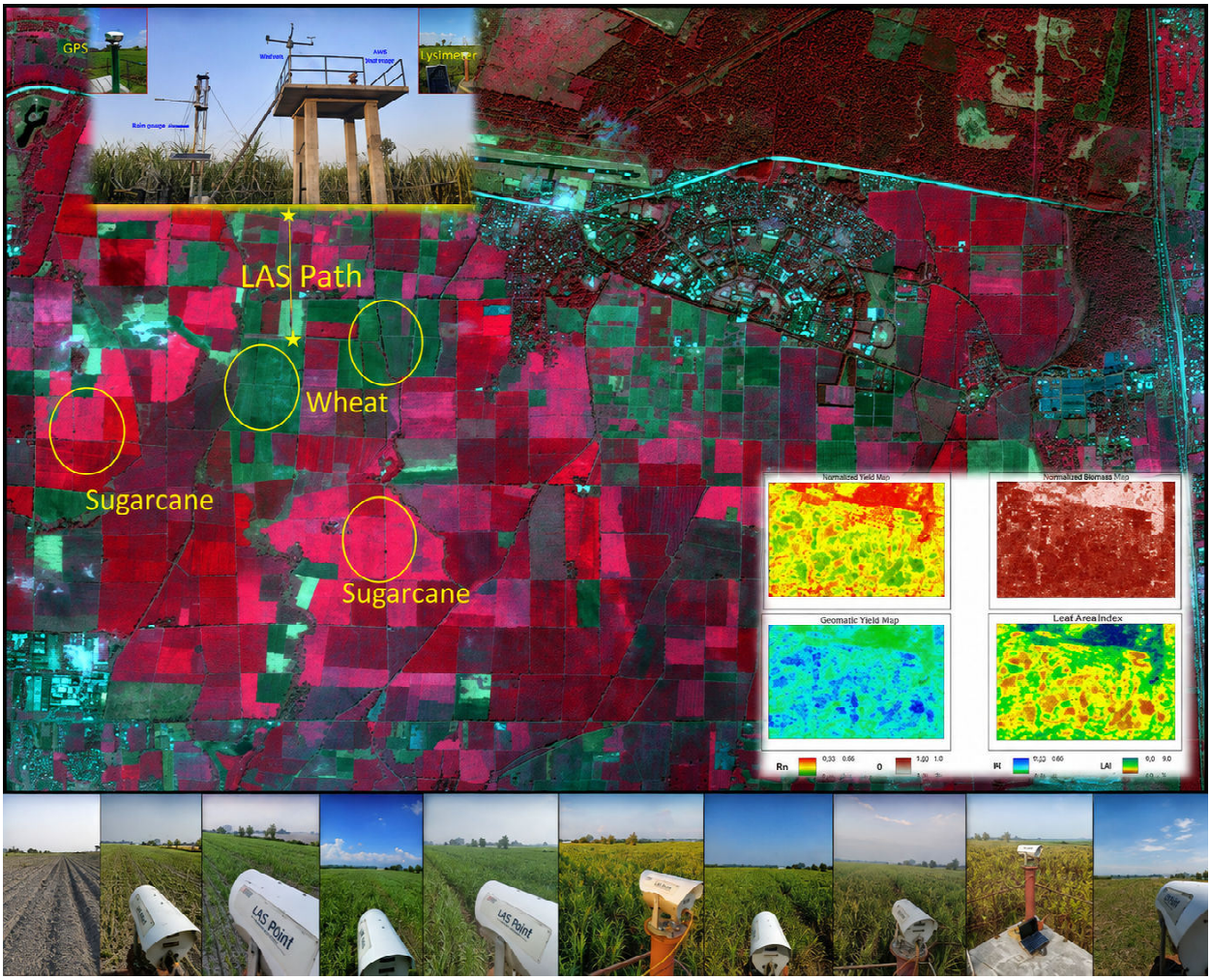


Fig. 6: Schematic diagram of LAS based measurement and RSEB based METRIC model estimation of evapotranspiration in Pantnagar (Source: Danodia *et al*., 2024)

crop water use and irrigation requirements. Surface energy balance models such as S-SEBI, MPT, SEBAL and METRIC integrate remote sensing and GIS for spatial ET mapping (Danodia *et al*., 2024; Satpathi *et al*., 2024a; Danodia *et al*., 2019). Danodia *et al.* (2024) analysed ET and surface energy fluxes in the Pantnagar region during the post-monsoon season using remote sensing data, a large aperture scintillometer (LAS) based ET measurement system and the METRIC model. The model produced ET estimates that closely matched ground observations, demonstrating its reliability and accuracy for regional-scale ET assessment (Fig. 6). AI and ML approaches improve evapotranspiration estimation and irrigation management by analysing weather, crop and soil moisture datasets (Satpathi *et al*., 2024b). These technologies contribute significantly to sustainable and climate-smart water resource management.

Challenges

Despite the recent advancement of geospatial technology and AI applications in agriculture, few major challenges still limit their large-scale operational implementation. One of the major constraints is the issue of data quality and labelling, as ML and DL models require large volumes of accurately labelled datasets for model formation and validation. In agricultural regions, especially in developing countries, inconsistent field records and limited annotation datasets reduce model performance and compromise its capability. Cloud

Table 6: List of different theme wise Govt. programmes and sponsored ministry/ agency and their details

Theme	Programme / Scheme	Sponsored Ministry/ Agency	Objective	Webpage/ URL
Farmer Digital Registry *and* Spatial Database	AgriStack	Ministry of Agriculture *and* Farmers Welfare	Create farmer-centric digital public infrastructure with geo-referenced databases	https://agristack.gov.in/#/
Decision Support *and* Spatial Intelligence	Krishi Decision Support System	Ministry of Agriculture *and* Farmers Welfare	Integrate satellite, weather, soil and crop data for agricultural planning	https://krishi-dss.gov.in/krishi-dss/
Crop Insurance *and* Risk Assessment	Pradhan Mantri Fasal Bima Yojana (PMFBY)	Ministry of Agriculture *and* Farmers Welfare	Provide crop insurance using technology-driven yield assessment	https://pmfby.gov.in/
Crop Forecasting *and* Production Estimation	FASAL Programme	Department of Agriculture *and* Farmers Welfare and Indian Space Research Organisation	Forecast crop production using satellite and agrometeorological data	https://www.ncfc.gov.in/fasal.html
Horticulture Monitoring	CHAMAN	Ministry of Agriculture *and* Farmers Welfare	Use geoinformatics for horticulture assessment and management	https://www.ncfc.gov.in/chaman.html
Soil Resource Mapping	Soil Health Card Scheme	Ministry of Agriculture *and* Farmers Welfare	Assess and monitor soil fertility status	https://soilhealth.dac.gov.in/home
Precision Irrigation *and* Water Management	Pradhan Mantri Krishi Sinchayee Yojana (PMKSY)	Ministry of Jal Shakti and Ministry of Agriculture *and* Farmers Welfare	Improve irrigation efficiency and water-use management	https://pmksy.mowr.gov.in/
Watershed *and* Natural Resource Management	Watershed Development Component of PMKSY	Department of Land Resources	Sustainable management of land and water resources	https://wdcpmksy.dolr.gov.in/
Agricultural Market Intelligence	e-NAM	Ministry of Agriculture *and* Farmers Welfare	Create a unified digital agricultural market platform	https://enam.gov.in/web/
Village-Level Resource Mapping	Digital General Crop Estimation Survey (DGCES)	Ministry of Agriculture *and* Farmers Welfare	Improve crop estimation using digital and geospatial tools	https://gces.dac.gov.in/#/
Agricultural Advisory Services	Bharat-VISTAAR	Ministry of Agriculture *and* Farmers Welfare	Provide AI-driven multilingual agricultural advisories	https://vistaar.da.gov.in/

cover in optical satellite imagery is another significant challenge, particularly during monsoon seasons and cloudy weather conditions, which restricts continuous crop monitoring and time-series analysis. Although SAR-based sensors partially overcome this limitation, however their processing

complexity and interpretation remain challenging for many users. Model interpretability is also an important concern, as advanced AI and DL models often function as black-box systems, making it difficult to explain the processes and limiting trust among stakeholders and policymakers. Another major challenge is the scalability of geospatial analytics for small and fragmented farms, which are common in countries like India. Furthermore, the lack of sufficient ground truth data for calibration and validation remains a critical limitation in many agricultural applications, affecting the accuracy of crop mapping, yield prediction and soil assessment models. Therefore, improving data accessibility, cloud-free observations, explainable AI approaches, affordable computing infrastructure and field-level validation mechanisms is essential for the sustainable and scalable adoption of geospatial analytics in smart agriculture.

Digital twins and AI-enabled predictive decision support are emerging rather than universally operational technologies in agriculture. Recent studies have demonstrated digital-twin concepts for irrigated agriculture, crop management and pest management by linking EO, IoT/field observations, models and machine learning, but large-scale agricultural deployment remains constrained by data interoperability, model updating, uncertainty, computational requirements and the need for reliable real-time observations. In India, NITI Aayog (2025) has identified digital twins, predictive analytics, smart sensors and frontier AI as important components of future technology-led agricultural transformation. Therefore, the near-term research priority is not simply to build digital twins, but to establish interoperable data architectures, validated process models, uncertainty-aware AI, domain adaptation and farmer-centred decision workflows that can be demonstrated under diverse Indian farming conditions.

Current program of Ministry of Agriculture

The Ministry of Agriculture and Farmers Welfare (MoAFW) is implementing several programs for the betterment of farmers, including PM-KISAN for direct income support, Pradhan Mantri Fasal Bima Yojana (PMFBY) for crop insurance and the Soil Health Card Scheme for balanced fertilizer use. In addition, digital agriculture initiatives, precision farming and climate-resilient agricultural practices are being promoted to enhance productivity, sustainability and farmers' income across the country. There are number of programmes which are currently functioning by agricultural ministry/ Government of India. The brief information is compiled in the Table 6.

FUTURE TRENDS

Recent advances in geospatial data analytics are supporting the transition toward more data-driven and climate-resilient agricultural monitoring. Technologies such as satellite and UAV remote sensing, AI/ML-based crop analytics, cloud computing and geospatial decision-support systems are already being demonstrated and increasingly applied for crop monitoring, yield prediction, irrigation and water management, soil assessment and pest-risk analysis. In India, these developments are reflected in ongoing applications of machine learning and multi-source geospatial datasets for crop classification, yield modelling, evapotranspiration estimation and agricultural risk assessment (Nihar *et al*., 2022; Danodia *et al*., 2025; Satpathi *et al*., 2024; Tiwari *et al*., 2025). However, their operational performance depends on representative training data, field validation, model transferability, computational resources and integration with decision-support systems.

In contrast, agricultural digital twins represent a relatively emerging research direction rather than a widely operational technology. Digital twins aim to dynamically represent agricultural systems by integrating sensor observations, satellite/UAV data, weather and soil information, crop models and AI-based analytics to support simulation and predictive decision-making (Subeesh and Chauhan, 2026). Recent literature shows demonstrations in crop monitoring, irrigation, controlled environments and farm-management applications, but large-scale deployment remains constrained by data interoperability, real-time data integration,

computational requirements, standardized architectures and limited field-scale validation. In the Indian context, digital twins, agentic AI and predictive analytics are identified as frontier technologies with future potential rather than universally deployed agricultural systems in the NITI Aayog roadmap for technology-led agricultural transformation (NITI Aayog, 2025). Thus, future research should focus on validated integration of EO, UAV, IoT, crop models and AI, with particular emphasis on interoperability, uncertainty assessment, scalability and farmer-oriented decision support.

CONCLUSION

The rapid advancement of geospatial technologies, UAV imaging and AI/ML has transformed modern agriculture from conventional practices toward smart and precision farming systems. The amalgam of satellite observations, drone-based sensing, spatial analytics and cloud computing platforms has enabled efficient monitoring of crops, soil, water resources and climatic variability at multiple spatial and temporal scales. Geospatial data analytics has significantly improved applications such as crop type classification, digital soil mapping, crop yield prediction, disease and pest detection, soil moisture estimation and agricultural water management. Advanced spectral indices, hyperspectral sensing, SAR observations and AI-driven predictive models are increasingly supporting real-time agricultural decision-making and resource optimization.

In India, the growing adoption of digital agriculture initiatives, precision farming techniques and government-supported geospatial programmes demonstrates the increasing importance of spatial technologies in ensuring food security and sustainable agricultural development. UAV-based sensing, IoT-enabled farm monitoring and cloud-based platforms such as Google Earth Engine are enabling high-resolution, near real-time agricultural assessment and operational monitoring. Despite challenges related to data quality, cloud contamination, lack of ground truth data, computational requirements and scalability for smallholder farms, continuous advancements in AI, big data analytics and sensor technologies are improving the reliability and operational utility of geospatial applications.

Future agricultural systems are expected to move toward multimodal, intelligent and climate-resilient farming frameworks integrating satellite data, UAV observations, weather forecasts, digital twins, AI-driven analytics and automated decision support systems. Real-time farm monitoring, predictive crop modelling and climate-smart agriculture will play a critical role in minimizing production risks and improving resource-use efficiency under changing climatic conditions. Overall, AI and geospatial technologies are revolutionizing agriculture by enhancing productivity, sustainability, precision resource management and evidence-based decision-making. Their continued integration into agricultural research, policy planning and farm management will be essential for achieving sustainable food production and resilient agricultural systems in the future.

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