From Digital Agricultural Governance to Intelligent Precision Farming: Repositioning E-Peek Pahani as an AI-Driven Ecosystem

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Abstract: ***Digital agriculture is transforming conventional farming through the integration of Artificial Intelligence (AI), geospatial technologies, Internet of Things (IoT), computer vision, and data-driven agricultural governance systems. In India, government-led initiatives such as the Digital Agriculture Mission, AgriStack, Bharat-VISTAAR, and the Maharashtra Government's E-Peek Pahani platform have significantly strengthened agricultural digitization and crop survey modernization. However, most existing systems continue to function primarily as administrative record management infrastructures and underutilize the intelligence potential of large-scale agricultural datasets. This paper critically examines the evolutionary trajectory of digital agriculture through the conceptual framework proposed by Wang et al., encompassing the phases of technological germination, mechanization, information integration, and intelligent leap. The study strategically positions E-Peek Pahani as a participatory geo-spatial agricultural governance infrastructure integrating geo-tagged crop imagery, land-linked agricultural metadata, and farmer-generated field intelligence within a large-scale digital ecosystem. Furthermore, the paper proposes a comprehensive AI-driven transformation framework incorporating computer vision, object detection architectures, geospatial intelligence, predictive analytics, explainable Artificial Intelligence, multilingual farmer advisory systems, and governance analytics to reposition E-Peek Pahani from an administrative crop survey platform toward an intelligent precision agriculture and AI-enabled governance ecosystem. The proposed framework demonstrates how public digital agriculture infrastructures can support automated crop monitoring, intelligent crop verification, precision farming, and AI-enabled agricultural governance. The study contributes toward understanding the future role of scalable AI-driven public agricultural ecosystems in sustainable digital agriculture and precision farming in India.***

Keywords: Digital Agriculture; Precision Agriculture; Artificial Intelligence; E-Peek Pahani; Agricultural Governance; Computer Vision

1. Introduction

The accelerating advancement of digital technologies has significantly transformed modern agricultural ecosystems through the integration of Artificial Intelligence (AI), Internet of Things (IoT), remote sensing, cloud computing, geo-spatial systems, and mobile-enabled agricultural platforms [1][2]. These technologies are increasingly supporting precision agriculture, crop monitoring, intelligent resource management, and data-driven agricultural governance aimed at improving productivity, sustainability, and operational efficiency.

Artificial Intelligence and computer vision technologies are increasingly emerging as central components of modern precision agriculture systems, supporting automated agricultural monitoring, predictive analytics, and intelligent decision-support mechanisms [3][4]. Recent studies further emphasize that future digital agriculture must evolve beyond purely efficiency-driven systems toward integrated and sustainable technology–economy–society ecosystems supported by lightweight computing infrastructures, interoperable multi-modal agricultural data systems, and human-centric intelligent agricultural governance frameworks [2]. Detailed technological discussions related to AI-driven agricultural intelligence are presented in subsequent sections of this paper.

In India, digital agriculture has gained strategic importance through government-led agricultural digitization initiatives emphasizing mobile governance, geo-spatial agricultural monitoring, integrated agricultural databases, and technology-enabled agricultural administration [5][6]. Initiatives such as NeGP-A AgriStack, IDEA, and the Digital Agriculture Mission aim to establish interoperable digital agricultural infrastructures capable of supporting efficient governance and future intelligent agricultural services [6][7][8][9].

Within this evolving digital agriculture ecosystem, the Maharashtra Government's E-Peek Pahani platform can be conceptually positioned as a state-level geo-spatial agricultural governance platform aligned with the broader objectives of the IDEA framework, AgriStack infrastructure, and the Digital Agriculture Mission, contributing toward interoperable, data-driven, and AI-enabled digital agriculture ecosystems in India [10]. The platform integrates geo-tagged crop imagery, land-linked agricultural metadata, and mobile-enabled farmer participation mechanisms to support digital crop verification and agricultural record management. Although E-Peek Pahani has substantially strengthened agricultural digitization and geo-spatial governance, its current utilization remains primarily administrative and documentation-oriented. The large-scale agricultural datasets generated through the platform remain underutilized for AI-driven agricultural intelligence, precision farming, predictive analytics, and intelligent decision-support applications [11][2].

This gap between large-scale agricultural digitization and intelligent agricultural utilization forms the central motivation of the present study. The research investigates

how existing public agricultural governance infrastructures can evolve toward AI-enabled precision agriculture ecosystems through the integration of computer vision, object detection, predictive analytics, geo-spatial intelligence, and intelligent agricultural governance mechanisms.
Accordingly, the objectives of this study are:
1) To analyze the evolution of digital agriculture toward intelligent AI-driven agricultural ecosystems.
2) To examine the role of E-Peek Pahani within digital agricultural governance in India.
3) To investigate the integration of AI, computer vision, predictive analytics, and geo-spatial intelligence within agricultural governance infrastructures.
4) To propose an AI-driven conceptual framework for extending E-Peek Pahani toward intelligent precision agriculture.

The major contribution of this paper lies in proposing a conceptual AI-enabled transformation framework for E-Peek Pahani based on the evolutionary stages of digital agriculture proposed by Wang et al. [1]. The study positions E-Peek Pahani across the phases of technological germination, mechanization, information integration, and intelligent leap while proposing an integrated architecture for AI-driven agricultural governance, precision farming, and intelligent agricultural decision support in India.

2. Literature Review

This section reviews the existing literature related to digital agriculture, Artificial Intelligence (AI), computer vision, and digital agricultural governance. The review examines the technological evolution of modern agriculture from digitization toward intelligent precision farming while highlighting the growing role of geo-spatial systems, AI-enabled analytics, and governance-oriented agricultural infrastructures. Particular emphasis is placed on the Indian agricultural context and the emerging relevance of platforms such as E-Peek Pahani within integrated digital agriculture ecosystems.

2.1 Digital Agriculture

The emergence of digital agriculture has significantly transformed traditional farming practices through the integration of Artificial Intelligence (AI), Internet of Things (IoT), cloud computing, remote sensing, and data-driven agricultural intelligence systems. Recent studies indicate that modern agricultural ecosystems are increasingly shifting from conventional crop monitoring approaches toward intelligent, predictive, and autonomous farming infrastructures [1]. Technologies such as AI-enabled crop analytics, smart sensing systems, blockchain-enabled traceability, and precision agriculture platforms are becoming central to sustainable agricultural development worldwide [1].

In the Indian context, digital agriculture is increasingly emerging as a strategic necessity for ensuring food security, climate resilience, and sustainable agricultural governance. Recent studies highlight that Information and Communication Technologies (ICT), mobile-enabled agricultural systems, and data-driven governance frameworks are playing a crucial role in improving agricultural productivity, farmer awareness, and rural sustainability in India [12]. Simultaneously, national discussions on agricultural modernization increasingly emphasize the importance of Artificial Intelligence, geo-spatial technologies, and integrated agricultural data infrastructures in strengthening precision farming and agricultural decision-making. A recent article published in The Economic Times [13] observed that India cannot afford to miss the ongoing AI transformation in agriculture, particularly in areas such as crop monitoring, climate-risk management, resource optimization, and precision farming. The article further emphasizes that large-scale public agricultural datasets, digital governance platforms, and interoperable agricultural ecosystems will become critical foundations for scalable AI-enabled agriculture in India. This evolving landscape has accelerated the adoption of integrated digital agriculture initiatives involving mobile governance, geo-spatial crop monitoring, and technology-enabled agricultural administration across multiple Indian states [12].

One such significant initiative is the Maharashtra Government's E-Peek Pahani platform, which enables farmers to digitally upload crop details along with geo-tagged field images and seasonal agricultural information. Although the platform successfully digitizes crop survey operations and creates a large repository of agricultural field-level data, the current utilization of this data remains predominantly transactional and documentation-oriented. The collected data possesses substantial untapped potential for developing scalable AI-driven agricultural intelligence systems.

Recent advancements in multi-modal sensing and deep learning-based agricultural monitoring further strengthen the possibility of extending E-Peek Pahani into a more integrated digital agriculture ecosystem. Multi-modal agricultural sensing approaches integrating drone-based radar systems, RGB-thermal imagery, and deep learning models have demonstrated effective soil moisture estimation and environmental monitoring capabilities [14]. Such approaches indicate that combining geo-tagged field imagery with contextual agricultural information can significantly enhance agricultural decision-making processes. Similarly, computer vision and image-analysis techniques are increasingly being explored for crop monitoring and agricultural assessment applications [15].

The geo-tagged agricultural images and crop metadata collected through E-Peek Pahani can therefore support future agricultural analytics, crop monitoring frameworks, and data-driven agricultural governance mechanisms. Furthermore, the integration of AI, IoT, geospatial analytics, and computer vision within public agricultural digital infrastructure can contribute toward sustainable farming practices, improved resource optimization, and more efficient agricultural administration.

Consequently, E-Peek Pahani presents a significant opportunity to evolve beyond a crop registration platform into a broader digital agricultural infrastructure capable of supporting smart agriculture and sustainable rural development in India.

2.2 AI and Computer Vision in Agriculture

Artificial Intelligence (AI) is increasingly becoming a foundational technology in precision agriculture, supporting data-driven crop monitoring, irrigation management, yield estimation, and agricultural decision-making through machine learning, computer vision, and predictive analytics. Recent advancements in agricultural AI and computer vision have accelerated the development of automated agricultural monitoring systems capable of real-time field analysis and intelligent resource optimization [13][16]. Contemporary research further highlights the growing role of AI-enabled sensing, visual analytics, and integrated digital agriculture frameworks in strengthening sustainable and precision-oriented farming ecosystems [17][18].

Machine learning techniques are increasingly being applied in agriculture for predictive modeling, crop classification, yield forecasting, soil analysis, and climate-aware agricultural planning [4]. Supervised learning models such as Support Vector Machines (SVM), Random Forests, Decision Trees, and Artificial Neural Networks (ANNs) have demonstrated effectiveness in agricultural prediction tasks involving crop productivity estimation, disease classification, and soil parameter analysis [19][20]. These approaches enable the extraction of meaningful agricultural patterns from large-scale heterogeneous datasets, thereby supporting evidence-based agricultural management.

The emergence of deep learning has further transformed agricultural data analysis by enabling automated feature extraction and high-dimensional image processing [21]. Convolutional Neural Networks (CNNs) have become particularly important in agricultural computer vision applications because of their ability to identify complex visual patterns within crop imagery and remote sensing datasets [22]. CNN-based architectures are increasingly utilized for crop monitoring, plant species recognition, fruit counting, weed detection, nutrient analysis, and crop maturity assessment [23][24]. Compared to conventional image processing methods, deep learning models provide improved robustness, scalability, and classification accuracy under varying environmental conditions.

Computer vision has therefore become a major technological component of modern agricultural monitoring systems. Agricultural computer vision applications primarily involve automated interpretation of visual agricultural data collected through smartphones, drones, satellites, field cameras, and IoT-enabled sensing devices [21][25]. These systems support crop monitoring through real-time visual analysis of plant conditions, soil variations, and environmental changes. The integration of image processing with AI-driven analytics has substantially improved precision agriculture capabilities across global agricultural ecosystems [2][26].

Object detection algorithms have gained significant importance in precision agriculture because of their capability to identify and localize agricultural objects within field images and remote sensing datasets. Deep learning-based object detection architectures such as YOLO (You Only Look Once), Faster R-CNN, SSD (Single Shot Detector), and RetinaNet are increasingly utilized for weed identification, fruit detection, pest monitoring, crop counting, and crop analysis [25][27][28]. Among these, YOLO-based architectures are widely preferred for real-time agricultural applications because of their computational efficiency and high-speed object recognition capabilities [25]. Similarly, Faster R-CNN models provide highly accurate region-based object identification suitable for detailed agricultural image analysis [27].

Semantic segmentation techniques have further enhanced agricultural image analysis by enabling pixel-level classification of crop imagery. Models such as U-Net, Mask R-CNN, DeepLab, and SegNet are increasingly utilized for plant segmentation, canopy mapping, leaf analysis, and agricultural field boundary identification [29][30]. Semantic segmentation approaches are particularly valuable in precision agriculture because they enable detailed spatial understanding of crop structures and field-level variations. Recent research in apple disease analysis demonstrates that segmentation-based approaches significantly improve image interpretation accuracy [15].

The increasing availability of drone imagery, satellite imaging, and multi-modal sensing systems has further expanded the role of AI in agricultural monitoring. Remote sensing technologies integrated with machine learning algorithms facilitate large-scale crop assessment, soil moisture estimation, vegetation analysis, and environmental monitoring [31][32]. Multi-modal agricultural sensing frameworks combining RGB imagery, thermal sensing, radar imaging, and geospatial analytics have demonstrated strong capabilities in crop stress analysis and precision irrigation management [31]. Such systems provide scalable solutions for agricultural data generation at both farm and regional levels.

Artificial Intelligence is also increasingly integrated with Internet of Things (IoT) infrastructures to support smart farming ecosystems. IoT-enabled agricultural systems utilize distributed sensors, automated monitoring devices, and cloud-connected analytics platforms to continuously collect environmental and agricultural data [33]. The integration of AI with IoT supports irrigation management, climate-adaptive farming, automated greenhouse monitoring, and agricultural resource optimization [34]. These systems improve agricultural efficiency while reducing operational limitations associated with conventional farming practices.

Another important advancement in AI-driven agriculture is the application of predictive analytics and time-series modeling for agricultural forecasting. Long Short-Term Memory (LSTM) networks, recurrent neural networks, and hybrid machine learning models are increasingly utilized for rainfall prediction, crop yield forecasting, pest outbreak analysis, and climate risk assessment [35][36]. Such predictive modeling approaches support proactive agricultural planning and resource allocation.

In recent years, explainable and trustworthy AI has also emerged as an important research direction within agricultural intelligence systems [37][38]. Since agricultural decision-making directly affects farmer livelihoods and food security, explainability and transparency of AI-generated outputs are increasingly recognized as important requirements for practical adoption. Explainable AI techniques such as SHAP, Grad-CAM, saliency maps, and interpretable machine learning models are therefore being integrated into agricultural analytics systems to improve transparency and reliability [37].

In the Indian agricultural context, AI-driven precision agriculture is gradually emerging through government initiatives, smart farming programs, digital agriculture missions, and technology-enabled agricultural governance frameworks [6][11]. However, the practical implementation of large-scale AI-enabled agricultural systems remains limited due to fragmented agricultural datasets, infrastructural constraints, limited farmer accessibility, and insufficient integration between digital governance systems and agricultural analytics platforms [11].

The integration of AI, computer vision, predictive analytics, remote sensing, and IoT technologies provides a strong technological foundation for modern digital agriculture systems. Platforms such as E-Peek Pahani can potentially utilize geo-tagged agricultural datasets and crop metadata to support future agricultural monitoring, crop analysis, and digital governance applications [13][10].

2.3 Digital Agricultural Governance in India

Digital agricultural governance in India has emerged as a critical component of national agricultural modernization strategies aimed at improving agricultural administration, farmer service delivery, resource management, and data-driven policymaking. The increasing integration of Information and Communication Technologies (ICT), digital governance frameworks, geo-spatial systems, and mobile-enabled agricultural services has significantly transformed the manner in which agricultural information is collected, managed, and utilized within the Indian agricultural ecosystem [5][6]. Recent developments in digital agriculture indicate a gradual transition from conventional administrative mechanisms toward interconnected and technology-driven agricultural governance infrastructures [1][2].

The evolution of digital agricultural governance in India initially focused on improving agricultural information dissemination and administrative accessibility through ICT-enabled platforms. Early e-governance initiatives such as the National e-Governance Plan in Agriculture (NeGP-A) emphasized digitization of agricultural records, online farmer services, crop advisory dissemination, and electronic agricultural databases [7]. These initiatives established foundational digital infrastructures for agricultural administration while promoting transparency, operational efficiency, and accessibility of agricultural information across rural regions [5].

Subsequently, India's digital agriculture ecosystem expanded significantly through national-level initiatives such as the Digital Agriculture Mission, India Digital Ecosystem of Agriculture (IDEA), AgriStack, and Smart Agriculture frameworks [6][9]. These initiatives emphasized the development of integrated agricultural information infrastructures capable of connecting farmer identities, land records, crop databases, financial services, satellite imagery, weather systems, and geo-spatial agricultural datasets through interoperable digital platforms [11]. Such frameworks aim to strengthen coordination, traceability, and efficiency within agricultural governance and service delivery systems [39].

A major characteristic of digital agricultural governance in India is the increasing adoption of mobile-enabled agricultural service delivery systems. Smartphone-based agricultural applications now support crop registration, subsidy distribution, market information dissemination, weather forecasting, crop insurance validation, and agricultural advisories [8][33]. Mobile governance mechanisms have improved accessibility of agricultural services, particularly in rural regions where conventional agricultural extension systems face operational limitations [40]. The integration of mobile technologies within agricultural governance therefore represents an important step toward decentralized digital agricultural administration.

Geo-spatial technologies and digital land governance systems have also become central components of modern agricultural administration in India. The integration of Geographic Information Systems (GIS), GPS-enabled agricultural monitoring, satellite imagery, and digital land record management systems has improved crop verification, agricultural planning, and resource monitoring capabilities [10]. Geo-spatial agricultural governance frameworks support scalable agricultural management by enabling location-aware crop surveys, spatial crop mapping, and digital verification of agricultural activities [41]. Such systems are particularly important for supporting crop insurance schemes, disaster compensation mechanisms, and agricultural subsidy distribution processes.

Recent policy discussions in India increasingly emphasize the role of Artificial Intelligence, machine learning, and predictive analytics in strengthening agricultural governance systems [11]. AI-enabled agricultural governance frameworks are being explored for crop monitoring, yield prediction, disease surveillance, climate risk assessment, and agricultural planning [26]. However, despite significant policy emphasis on AI-driven agriculture, the practical integration of advanced analytics within public agricultural governance infrastructures remains limited. Existing agricultural digital systems often function primarily as administrative record management platforms rather than comprehensive data-driven agricultural intelligence systems [2].

Within this broader governance landscape, the Maharashtra Government's E-Peek Pahani platform represents an important example of digital agricultural administration at the state level. The platform enables digital crop survey operations through mobile-based crop information submission, geo-tagged field images, and integration with land record systems [10]. By combining mobile governance mechanisms with geo-spatial agricultural verification, the platform modernizes conventional crop survey and agricultural record management processes.

Despite these advancements, digital agricultural governance systems in India continue to face several challenges related to infrastructure availability, digital literacy, interoperability, data quality, farmer accessibility, and institutional coordination [40][41]. Additionally, the transition from administrative digitization toward integrated data-driven governance requires stronger coordination between agricultural data infrastructures, analytical systems, and digital service delivery frameworks [11].

Consequently, digital agricultural governance in India is gradually evolving from isolated e-governance initiatives toward integrated digital agricultural administration systems. National initiatives such as NeGP-A, IDEA, AgriStack, and the Digital Agriculture Mission, along with state-level platforms such as E-Peek Pahani, demonstrate the growing importance of ICT-enabled governance, geo-spatial integration, and mobile-based agricultural administration within the Indian agricultural ecosystem.

3. Evolutionary Analysis of E-Peek Pahani within Digital Agriculture

This section discusses the evolutionary progression of digital agriculture based on the framework proposed by Wang et al. The analysis examines the transition from foundational agricultural digitization toward mechanized systems, integrated digital governance infrastructures, and intelligent AI-driven agricultural ecosystems. Each stage is further contextualized within the Indian agricultural landscape by examining the role of E-Peek Pahani as an emerging geo-spatial agricultural governance platform supporting the evolution toward precision agriculture and intelligent digital farming.

3.1 Technological Germination

The technological germination phase of digital agriculture represents the earliest transition from conventional agricultural practices toward digitally assisted agricultural governance and information management systems. According to Wang et al. [1], this phase was characterized by the introduction of foundational digital technologies aimed at improving agricultural documentation, information accessibility, communication efficiency, and administrative coordination. In India, this transition emerged through the adoption of Information and Communication Technologies (ICT), e-governance initiatives, and digitized agricultural record management systems designed to support agricultural administration and farmer-oriented service delivery [5][7].

During this initial phase, digital transformation in agriculture primarily focused on replacing fragmented manual processes with electronic information systems capable of enhancing data collection, agricultural monitoring, and administrative efficiency. Government-led initiatives such as the National e-Governance Plan in Agriculture (NeGP-A) played a significant role in establishing the technological foundation for digital agricultural ecosystems in India [7]. These initiatives encouraged the development of electronic crop records, agricultural databases, and mobile-enabled information dissemination systems. The broader objective during this stage was the digitization of agricultural workflows and improved accessibility of agricultural information for governance and planning purposes rather than intelligent agricultural automation [5].

The increasing adoption of mobile technologies, geo-tagging mechanisms, and digital agricultural records gradually strengthened the shift from isolated manual systems toward coordinated digital agricultural administration [6][8]. Early ICT-enabled agricultural platforms established the basic technological infrastructure necessary for large-scale agricultural data collection and electronic governance mechanisms within the Indian agricultural ecosystem.

Within this broader context of agricultural digitization, the Maharashtra Government's E-Peek Pahani platform represents a significant example of technological germination in agricultural governance at the state level. The platform introduced a mobile-enabled digital crop survey mechanism that allows farmers to upload crop details, field photographs, seasonal crop information, and geo-tagged agricultural records directly through smartphones. By digitizing traditional crop inspection and registration processes, E-Peek Pahani reduced dependency on fully manual field surveys while simultaneously creating a large-scale repository of field-level agricultural data.

The significance of E-Peek Pahani during this phase lies in its introduction of participatory digital governance within agricultural data collection systems. Unlike earlier administrative mechanisms that relied primarily on centralized reporting structures, the platform enabled farmers to directly contribute crop information and geo-spatial agricultural evidence through mobile applications. This aligns with the broader technological germination phase described by Wang et al. [1], where early-stage digital systems primarily function as foundational agricultural information infrastructures.

At this stage, E-Peek Pahani primarily functioned as a digitized crop documentation and reporting mechanism rather than an intelligent agricultural system.

Despite its successful digitization of crop survey operations, the present implementation of E-Peek Pahani remains largely focused on administrative documentation, crop registration, and verification-oriented governance processes. The collected geo-tagged images, crop metadata, and seasonal agricultural information are primarily utilized for record management and agricultural administration. Nevertheless, the platform established a foundational digital infrastructure for large-scale agricultural data generation and digital crop governance in India.

Therefore, within the evolutionary framework proposed by Wang et al. [1], E-Peek Pahani can be viewed as a significant agricultural digitization initiative emerging from the technological germination phase of digital agriculture. Its electronic crop records, mobile-enabled agricultural reporting mechanisms, geo-tagged field data, and farmer participation framework collectively represent the foundational stage of digital agricultural governance evolution in India.

3.2 Mechanization

The mechanization phase of digital agriculture represents the transition from foundational digitization toward technology-enabled automation of agricultural operations, monitoring

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systems, and governance workflows. According to Wang et al. [1], this stage is characterized by the increasing adoption of mobile technologies, geo-spatial systems, digital verification mechanisms, and automated agricultural processes that improve operational efficiency while reducing dependency on conventional manual procedures. In India, digital agricultural mechanization emerged through automated crop survey systems, GPS-enabled agricultural monitoring, and technology-assisted governance infrastructures designed to improve agricultural administration and large-scale crop monitoring [10][11].

Traditional agricultural survey mechanisms in India largely depended on manual field inspections conducted by agricultural officers and revenue officials. These processes were labor-intensive, time-consuming, and difficult to scale across geographically dispersed agricultural regions. The introduction of mechanized digital agricultural systems significantly transformed these workflows through centralized agricultural data collection, location-aware verification systems, and electronically assisted crop surveys [10]. The mechanization phase reduced dependency on manual crop verification while simultaneously increasing scalability of agricultural data acquisition.

A major characteristic of this phase was the integration of geo-spatial technologies and GPS-enabled verification frameworks within agricultural governance systems. Geo-tagging capabilities facilitated location-aware crop verification, digital field mapping, and spatial validation of agricultural records [42]. The integration of GPS coordinates with field-level agricultural imaging and land record databases improved the reliability, traceability, and operational efficiency of agricultural survey processes. These developments represented a major shift from manually dependent agricultural administration toward digitally mechanized governance infrastructures [11][42].

Within this evolving mechanization ecosystem, the Maharashtra Government's E-Peek Pahani (ई-पीक पाहणी) platform represents a significant implementation of mechanized agricultural governance. The platform introduced smartphone-based crop survey operations that enabled farmers to upload crop information, seasonal agricultural records, and geo-tagged field photographs directly into centralized digital systems [10]. This mechanized workflow substantially reduced dependence on paper-based agricultural surveys and repetitive physical inspections while accelerating agricultural data collection across large rural regions.

One of the most important technological features of E-Peek Pahani is its GPS-based verification framework supporting geographically authenticated crop survey operations [10]. By integrating geo-tagged crop photographs with digital land records and survey identifiers, the platform established a more structured and traceable agricultural verification mechanism. This geo-spatial integration strengthened the reliability of agricultural records and contributed toward the creation of geographically referenced agricultural datasets for administrative monitoring and governance purposes.

E-Peek Pahani also demonstrates the role of mechanization in decentralizing agricultural data collection processes. Farmers directly contribute crop information and field-level evidence through mobile applications, thereby improving scalability and operational continuity within crop survey mechanisms. This transition from centralized manual inspection toward distributed digital reporting reflects a broader shift in Indian agricultural governance toward technology-enabled administrative modernization [10].

However, despite these advancements, the current implementation of E-Peek Pahani remains primarily focused on operational automation and administrative crop verification rather than advanced agricultural intelligence generation. The platform effectively mechanizes crop survey workflows and geo-spatial validation processes, but the collected datasets are still predominantly utilized for governance, record management, and verification-oriented administrative functions.

Therefore, within the evolutionary framework proposed by Wang et al. [1], E-Peek Pahani can be viewed as a mature example of mechanization in digital agricultural governance, where automation, centralized digital workflows, and geo-spatial verification mechanisms have substantially modernized agricultural data collection processes in India.

3.3 Information Integration

The information integration phase of digital agriculture represents the transition from isolated digital systems toward interconnected agricultural data ecosystems capable of supporting coordinated governance and data-driven agricultural administration. According to Wang et al. [1], this stage is characterized by the integration of multiple agricultural information streams, including land records, geo-spatial information, crop databases, farmer participation systems, and digital monitoring platforms into unified agricultural infrastructures. In India, this transition accelerated through initiatives promoting interoperable agricultural databases, digital land governance, and integrated agricultural information systems [9][10].

One of the defining characteristics of information integration in agriculture is the convergence of heterogeneous agricultural datasets into centralized digital infrastructures capable of supporting large-scale agricultural coordination [9][39]. Unlike earlier stages focused primarily on digitization and operational automation, this phase emphasizes interoperability among land records, crop information systems, geo-tagged agricultural data, weather information services, and mobile agricultural platforms [39]. Such integrated systems improve coordination between agricultural administration, crop monitoring, and governance workflows.

In the Indian agricultural context, initiatives such as the India Digital Ecosystem of Agriculture (IDEA), AgriStack, and the Digital Agriculture Mission promoted the development of integrated agricultural information architectures [6][9]. These initiatives aimed to connect farmer identities, land ownership records, crop metadata, geo-spatial datasets, and agricultural service infrastructures through interoperable digital governance systems [10][11]. National policy discussions increasingly recognized integrated agricultural data

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infrastructures as essential components of modern agricultural governance and digital agricultural administration [11].

Within this broader transition toward integrated digital agriculture, the Maharashtra Government's E-Peek Pahani platform represents a strong example of the information integration stage in Indian agricultural governance. The platform combines digital land records, geo-tagged crop imagery, seasonal crop metadata, farmer-submitted agricultural information, and mobile-based crop verification into a unified digital crop survey ecosystem. This integration enables the creation of continuously updated agricultural records combining spatial, visual, administrative, and field-level agricultural information within a centralized governance framework.

A key strength of E-Peek Pahani lies in linking geo-referenced agricultural imagery with land-linked crop records and farmer participation mechanisms. Farmers directly upload crop details and field photographs associated with specific land parcels, enabling more consistent and traceable agricultural record management. The integration of crop metadata, GPS coordinates, land ownership records, and field-level agricultural imagery creates a multi-dimensional agricultural dataset capable of supporting crop survey administration, subsidy verification, crop insurance validation, and regional agricultural planning.

Compared to fragmented and manually maintained agricultural records traditionally used in agricultural administration, E-Peek Pahani represents a substantial advancement toward centralized and interoperable agricultural governance. However, despite the successful integration of multiple agricultural information streams, the current implementation of the platform remains primarily focused on administrative coordination and digital record management rather than intelligent agricultural analytics.
Therefore, within the evolutionary framework proposed by Wang et al. [1], E-Peek Pahani can be strongly positioned within the information integration stage of digital agriculture. The platform establishes an interconnected agricultural governance ecosystem integrating land records, geo-spatial information, crop metadata, and farmer-generated agricultural data within a unified digital infrastructure.

3.4 Intelligent Leap: Toward AI-Driven Agricultural Intelligence

The intelligent leap phase represents the most advanced stage in the evolution of digital agriculture, characterized by the integration of Artificial Intelligence (AI), machine learning, computer vision, predictive analytics, Internet of Things (IoT), autonomous systems, and intelligent decision-support mechanisms into agricultural ecosystems. According to Wang et al. [1], this phase moves beyond digitization, mechanization, and information integration toward intelligent agricultural infrastructures capable of autonomous analysis, predictive reasoning, adaptive decision-making, and real-time agricultural support. Globally, digital agriculture is increasingly transitioning toward intelligent ecosystems where agricultural data is continuously analyzed to generate actionable agricultural intelligence [2][3].

Recent advancements in AI and precision agriculture have significantly transformed agricultural monitoring and farm-level decision-making processes. AI-driven agricultural systems increasingly utilize deep learning, remote sensing, computer vision, and predictive analytics for crop health assessment, irrigation optimization, yield forecasting, and environmental monitoring [4][21]. Technologies such as convolutional neural networks (CNNs), semantic segmentation frameworks, Vision Transformers, and object detection architectures including YOLO and Faster R-CNN are now widely applied for automated crop recognition, weed detection, pest identification, and field-level agricultural analysis [25][27]. These developments demonstrate the growing global transition toward data-driven precision agriculture systems.

Internationally, intelligent agriculture systems increasingly integrate multi-modal sensing technologies, drone-based imaging, IoT-enabled field sensors, geo-spatial analytics, and AI-driven predictive systems to support sustainable agricultural management [26]. Multi-modal agricultural intelligence frameworks combining RGB imaging, thermal sensing, radar systems, and machine learning algorithms have demonstrated strong capabilities in soil moisture estimation, crop stress analysis, and environmental monitoring [14]. Similarly, AI-enabled agricultural advisory systems are being developed to support intelligent irrigation scheduling, nutrient management, crop planning, and early risk identification [33].

Another important characteristic of the intelligent leap phase is the emergence of explainable and trustworthy AI systems. Modern agricultural AI frameworks increasingly emphasize explainability, transparency, and human-in-the-loop decision-making to improve reliability and adoption among farming communities [26]. Explainable AI techniques such as SHAP, Grad-CAM, saliency visualization, and interpretable machine learning models are becoming important components of intelligent agricultural systems, particularly in applications involving crop diagnosis, agricultural recommendations, and climate risk assessment [37][38].

In the Indian agricultural context, the transition toward intelligent digital agriculture is gradually emerging through national initiatives emphasizing AI-driven agricultural governance, precision farming, and smart agricultural ecosystems [11]. Policy frameworks such as the Digital Agriculture Mission and IDEA recognize the importance of AI, geospatial analytics, drone technologies, and integrated agricultural intelligence systems in improving agricultural productivity and governance efficiency [10][11]. Recent initiatives such as Bharat-VISTAAR further strengthen this transition by promoting multilingual AI-enabled agricultural advisory systems integrated with AgriStack and digital agricultural infrastructures [43]. However, despite increasing policy emphasis, large-scale intelligent agricultural implementations remain limited within existing public agricultural infrastructures.

Within this evolving landscape, the Maharashtra Government's E-Peek Pahani platform presents a highly significant opportunity for enabling the intelligent leap phase of digital agriculture in India. As discussed in the previous sections, E-Peek Pahani has already established an integrated agricultural information infrastructure containing geo-tagged crop images, land records, crop metadata, and mobile-enabled crop verification systems [10]. However, the current utilization of this data remains largely administrative and verification-oriented rather than intelligence-driven.

The geo-tagged agricultural datasets generated through E-Peek Pahani provide a strong foundation for the development of AI-driven agricultural intelligence systems. Farmer-uploaded field images and crop metadata can support computer vision pipelines for automated crop recognition, crop-stage identification, weed analysis, and crop health assessment [25][27]. Object detection and image classification models can enable automated analysis of field-level agricultural imagery, thereby reducing dependence on purely manual agricultural monitoring mechanisms.

Furthermore, the integration of geo-spatial agricultural data with predictive analytics models can support intelligent agricultural decision systems capable of crop-risk estimation, irrigation planning, environmental monitoring, and regional agricultural forecasting [26][33]. The combination of E-Peek Pahani datasets with weather information systems, remote sensing infrastructures, and IoT-enabled agricultural sensing technologies can significantly strengthen precision agriculture capabilities within the Indian agricultural ecosystem.

A future AI-enabled architecture built upon E-Peek Pahani can therefore function as an integrated agricultural intelligence ecosystem consisting of multiple interconnected components. At the data acquisition layer, geo-tagged field images, crop metadata, satellite imagery, weather datasets, and IoT sensor streams can be continuously collected and integrated. At the intelligence layer, machine learning and computer vision models can perform automated crop classification, object detection, anomaly identification, and predictive agricultural analytics. At the governance and advisory layer, intelligent dashboards and farmer-centric interfaces can support agricultural officers, policymakers, insurance agencies, and farmers through data-driven agricultural insights and decision-support mechanisms.

Such an AI-enabled governance framework can strengthen agricultural administration by supporting automated crop verification, regional crop intelligence generation, subsidy validation, and evidence-driven agricultural planning. Simultaneously, intelligent farmer support systems can provide localized crop monitoring insights, environmental alerts, irrigation recommendations, and field-level agricultural guidance through mobile platforms.

Importantly, E-Peek Pahani already possesses one of the most critical prerequisites for intelligent agriculture systems: large-scale agricultural data generation through continuous farmer participation [10]. The platform therefore provides not only a governance infrastructure but also a scalable public agricultural dataset capable of supporting future AI research, agricultural computer vision development, and intelligent agricultural analytics in India.

Nevertheless, several challenges must be addressed before E-Peek Pahani can fully transition toward the intelligent leap stage. These include variability in image quality, rural digital infrastructure limitations, multilingual accessibility requirements, explainability concerns, data privacy issues, and the need for scalable computational infrastructures [11][37]. The successful implementation of AI-driven agricultural governance also requires careful integration of technological innovation with institutional coordination, farmer trust, and policy support mechanisms.

Therefore, within the evolutionary framework proposed by Wang et al. [1], the future advancement of E-Peek Pahani depends on its transition from an integrated agricultural information platform toward an intelligent AI-driven agricultural ecosystem. The proposed transformation establishes a research-oriented framework in which AI, computer vision, predictive analytics, geospatial intelligence, and explainable decision-support systems collectively contribute toward precision agriculture, intelligent governance, and sustainable agricultural development in India.

4. Proposed AI-Driven Framework for E-Peek Pahani

The proposed AI-driven framework, as shown in Figure 1, repositions E-Peek Pahani from a digital crop survey platform into an intelligent agricultural governance ecosystem capable of supporting precision agriculture, automated crop intelligence, and data-driven agricultural decision-making. The framework utilizes geo-tagged crop imagery, land-linked agricultural metadata, farmer-generated field information, and geo-spatial governance infrastructures to establish a scalable public digital agriculture ecosystem.

The framework conceptualizes E-Peek Pahani as a multi-layered intelligent architecture integrating agricultural data acquisition, geo-spatial analytics, AI-driven processing, object detection systems, multilingual farmer advisory mechanisms, and governance-oriented agricultural intelligence modules. The proposed ecosystem supports automated crop monitoring, agricultural verification, environmental assessment, predictive agricultural analysis, and intelligent governance workflows.

4.1 Data Acquisition Layer

The Data Acquisition Layer forms the foundational component of the framework and supports large-scale agricultural data collection from multiple heterogeneous sources. The primary datasets include farmer-uploaded crop records, geo-tagged field photographs, crop metadata, seasonal agricultural information, and land-linked agricultural survey data collected through mobile platforms.
The framework further integrates satellite imagery, drone-based agricultural imaging, IoT-enabled field sensors, weather information systems, and remote sensing infrastructures to create a comprehensive agricultural intelligence repository. This layer establishes the digital and geo-spatial foundation for continuous agricultural monitoring and intelligent agricultural analytics.

4.2 Geo-Spatial Layer

The Geo-Spatial Layer integrates agricultural datasets with GIS infrastructures, GPS-enabled field mapping, geo-tagging systems, and spatial agricultural databases. The integration of geo-referenced crop imagery with land-linked agricultural records enables location-aware crop monitoring, field boundary verification, environmental assessment, and regional agricultural planning.

This layer also establishes interoperability with national digital agriculture ecosystems such as AgriStack, IDEA, and Bharat-VISTAAR through standardized geo-spatial agricultural data integration and governance-linked agricultural intelligence systems.

4.3 AI Processing Layer

The AI Processing Layer functions as the central intelligence component of the framework. This layer integrates machine learning, deep learning, predictive analytics, explainable AI, and computer vision techniques for automated agricultural analysis and intelligent decision support.

AI models can support crop recognition, crop-stage analysis, plant health assessment, irrigation prediction, climate-risk analysis, and agricultural forecasting using integrated multi-modal agricultural datasets. By combining crop imagery, geo-spatial information, weather datasets, and environmental sensing data, this layer transforms agricultural records into actionable agricultural intelligence systems.

4.4 Object Detection Layer

The Object Detection Layer focuses on automated visual agricultural analysis using AI-driven image interpretation and object detection models. The geo-tagged agricultural images generated through E-Peek Pahani can support automated identification of crops, weeds, agricultural anomalies, and field-level crop conditions.

This layer enables automated crop verification, crop-stage assessment, agricultural monitoring, and region-specific crop intelligence generation through large-scale agricultural image analysis. The integration of explainable AI mechanisms further improves transparency and reliability in AI-enabled agricultural decision-support systems.

4.5 Farmer Advisory Layer

The Farmer Advisory Layer delivers intelligent, localized, and multilingual agricultural assistance through AI-generated agricultural insights integrated with national advisory ecosystems such as Bharat-VISTAAR. The system combines predictive analytics, weather information, geo-spatial intelligence, environmental monitoring, and crop intelligence systems to generate data-driven agricultural advisories.

This layer supports irrigation planning, crop management, fertilizer utilization, environmental risk alerts, and climate-aware agricultural recommendations through mobile-enabled farmer interfaces. The objective is to transform agricultural datasets into personalized and actionable farmer-centric decision-support systems.

4.6 Governance Analytics Layer

The Governance Analytics Layer supports agricultural administration, governance validation, institutional agricultural intelligence generation, and evidence-based policymaking. Integrated agricultural datasets and AI-driven analytics can support crop verification, subsidy validation, disaster assessment, crop insurance monitoring, and regional agricultural planning.

The layer also incorporates explainable AI mechanisms to improve transparency, accountability, and reliability within AI-enabled agricultural governance frameworks. Such systems strengthen trust and operational efficiency within public agricultural infrastructures.

4.7 Integrated Intelligent Agricultural Ecosystem

The proposed framework ultimately positions E-Peek Pahani as a scalable geo-spatial agricultural governance and AI-enabled precision agriculture ecosystem aligned with India's emerging digital agriculture vision. Within this architecture, E-Peek Pahani functions as a state-level agricultural data acquisition and governance platform supporting automated crop verification, geo-spatial agricultural intelligence, and AI-driven analytics, while Bharat-VISTAAR functions as the national multilingual agricultural advisory and intelligent decision-support layer.

The framework demonstrates how existing public agricultural infrastructures can evolve toward integrated intelligent agricultural ecosystems through the convergence of geo-spatial governance, AI-driven analytics, object detection systems, predictive agricultural intelligence, multilingual advisory platforms, and governance-oriented agricultural analytics.

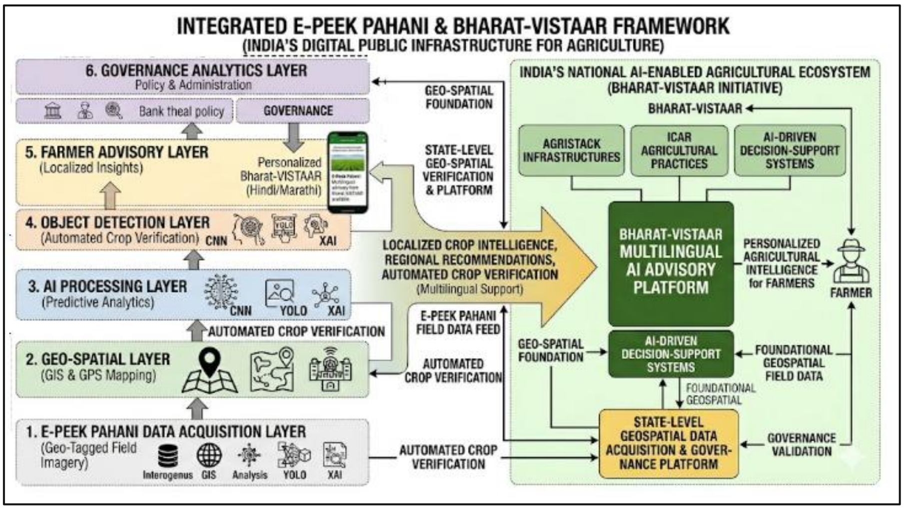

Figure 1: Proposed AI-Driven Multi-Layered Framework for Transforming E-Peek Pahani into an Intelligent Precision Agriculture and Governance Ecosystem Integrated with Bharat-VISTAAR, AgriStack, and Geo-Spatial Agricultural Intelligence Systems

5. Challenges and Research Opportunities

The transition from digital agricultural governance toward intelligent precision farming introduces several technological, infrastructural, operational, and research-related challenges. Although platforms such as E-Peek Pahani have established strong digital agricultural data infrastructures, multiple gaps remain in achieving scalable AI-enabled agricultural intelligence systems.

Key Challenges

Challenges

- Variability in geo-tagged crop imagery, inconsistent metadata, and heterogeneous field conditions affect the robustness and generalization capability of AI-based agricultural models.
- Limited internet connectivity, hardware constraints, and uneven digital literacy restrict large-scale deployment of intelligent agricultural systems in rural environments.
- Lack of interoperability among land records, geo-spatial platforms, crop databases, and weather information systems limits integrated agricultural intelligence generation.
- Processing large-scale agricultural imagery and geo-spatial datasets requires scalable cloud infrastructure and computationally efficient AI architectures.
- Explainability, transparency, and trustworthiness remain critical challenges in AI-driven agricultural decision-support systems.
- Secure management and ethical utilization of farmer-linked agricultural and geo-spatial data continue to raise governance and privacy concerns.
- Regional variability in climate, soil characteristics, crop patterns, and farming practices necessitates adaptive and localized AI models.

Research Opportunities

- Geo-tagged agricultural datasets provide significant opportunities for AI-driven crop recognition, crop-stage analysis, and automated agricultural monitoring.
- Integration of computer vision and object detection techniques can support intelligent crop verification, disease surveillance, and field-level agricultural analytics.
- Multi-modal agricultural intelligence systems combining smartphone imagery, satellite data, drone sensing, IoT devices, and geo-spatial analytics represent important future research directions.
- Explainable and farmer-centric AI frameworks can improve transparency, usability, and adoption of intelligent agricultural advisory systems.
- Predictive analytics and machine learning models can support yield forecasting, irrigation planning, crop-risk assessment, and climate-aware agricultural decision-making.
- Lightweight edge-AI and mobile intelligence frameworks present strong opportunities for deploying AI-driven agriculture in resource-constrained rural environments.
- Interoperable digital agriculture ecosystems integrating governance platforms, geo-spatial infrastructures, and precision farming systems can strengthen coordinated agricultural administration.
- AI-enabled governance analytics can support automated crop verification, subsidy validation, disaster assessment, and evidence-based agricultural policymaking.
- Integrated AI-driven precision agriculture systems can contribute toward sustainable farming, resource optimization, and climate-resilient agricultural management.

Overall, the evolution of digital agricultural platforms toward AI-driven precision farming presents significant opportunities for advancing intelligent agricultural governance, sustainable farming practices, and data-driven agricultural decision-making in India.

6. Conclusion

This paper proposed an AI-driven transformation framework for the Maharashtra Government's E-Peek Pahani platform by repositioning it from a digital crop documentation and verification system toward an intelligent precision agriculture and governance ecosystem. Using the evolutionary perspective of digital agriculture, the study demonstrated how geo-tagged crop imagery, land-linked agricultural metadata, mobile governance mechanisms, and participatory crop survey infrastructures can support advanced agricultural intelligence generation. The proposed framework integrates geo-spatial systems, Artificial Intelligence, computer vision, object detection, predictive analytics, multilingual farmer advisory systems, and governance analytics to enable automated crop monitoring, intelligent agricultural verification, precision farming support, and data-driven agricultural governance. The study further highlights that large-scale public digital agriculture platforms can function as foundational infrastructures for scalable AI-enabled agricultural ecosystems aligned with emerging national initiatives such as AgriStack, IDEA, Digital Agriculture Mission, and Bharat-VISTAAR. The proposed architecture, therefore, establishes a conceptual foundation for future research on intelligent agricultural governance, explainable agricultural AI, and sustainable precision agriculture systems in India.

Disclaimer

The proposed AI-driven framework presented in this study is a conceptual and research-oriented architecture developed for academic analysis purposes. The study does not represent an official implementation, policy recommendation, or endorsed technological roadmap of the Government of Maharashtra.

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