



Cybersecurity Challenges in Digital Agriculture: A Hybrid AI-Based Framework

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Abstract. Digital agriculture uses AI, ML, IoT, and precision farming to revolutionize farming. These technologies help sustainable agricultural growth by improving crop monitoring, irrigation management, disease detection, yield prediction, and resource optimization. However, smart farming ecosystems' growing dependency on linked digital systems has raised cybersecurity concerns about data privacy, unsecured IoT devices, unwanted access, and system stability. The biggest cybersecurity problems in digital agriculture and current advances in AI-enabled agricultural systems are examined in this systematic analysis of 2020–2026 research. The results show that AI models like CNNs, Random Forest, and XGBoost improve agricultural decision-making, predictive analytics, and operational efficiency. Scalability, interoperability, computational complexity, and data security challenges still plague large-scale deployment. A hybrid AI-based architecture incorporating safe data capture, blockchain-enabled data management, intelligent analytics, and decision-support systems improves digital agricultural cybersecurity and sustainability, according to the research. The framework promotes future agricultural growth with robust, secure, and efficient smart farming ecosystems.

Keywords: Agriculture, Precision Agriculture, Artificial Intelligence, Smart Agriculture, Hybrid AI Models, AI Based Predictive Models, Machine Learning Models

1 INTRODUCTION

Recently, digital agriculture has advanced the integration of AI, IoT, blockchain, and precision farming technologies to increase agricultural production, sustainability, and operational security. Modern research focuses on smart farming applications include AI-enabled crop monitoring, blockchain-based agricultural data management, IoT-supported irrigation systems, and deep learning for plant disease diagnosis and yield prediction. Convolutional Neural Networks (CNNs), YOLO models, Random Forests, and XGBoost are increasingly used to improve decision-making, automate farm activities,

and monitor agriculture in real time. Many research use experimental and data-driven methods to prove intelligent agriculture systems work. AI-driven frameworks increase disease diagnosis, irrigation efficiency, resource optimization, and predictive agriculture analytics, according to literature. However, cybersecurity risks, limited scalability, inadequate real-world implementation, interoperability limitations, and data privacy concerns continue to hinder safe smart farming system adoption. Thus, robust and trustworthy digital agricultural systems with AI-based analytics, secure data management, and intelligent decision-support mechanisms are needed [1] [2].

1.1 Research Objectives

1. To study AI, ML, IoT, and blockchain in digital agriculture and smart agricultural systems.
2. To assess AI-enabled agricultural technology' cybersecurity, operational, performance, and scalability problems.
3. To find safe, sustainable, and intelligent technologies to improve smart farming infrastructure, data security, and resilient digital agricultural ecosystems.

1.2 Scope of the Research

This study analyzes how AI, ML, IoT, blockchain, and precision farming make digital agriculture secure. Smart farming technologies, AI-enabled agricultural monitoring, intelligent irrigation systems, agricultural network cybersecurity, and data-driven decision-support mechanisms are examined in 2020–2026 research. Digital farming ecosystems' technology, cybersecurity, operational limits, and sustainable agricultural applications are examined in the article. This study promotes academic research, technological innovation, and policy development for secure, scalable, and resilient smart agricultural infrastructure [3].

1.3 Research Questions

- RQ1: Which AI and ML methods improve digital farm security, monitoring, and decision-making best?
- RQ2: How do cybersecurity, scalability, and infrastructure issues influence smart farming technology implementation?
- RQ3: What technologies and research can reinforce safe, scalable, and sustainable AI-enabled digital agricultural ecosystems?

2 LITERATURE REVIEW

2020–2026 literature suggests digital agriculture systems utilize AI, ML, IoT, and precision farming. Recent research recommends precision farming, climate-smart agriculture, smart irrigation, and biologically driven crop protection to increase agricultural productivity and resource efficiency. Deep learning, intelligent sensing, and automated

monitoring are used for agricultural disease detection, yield prediction, soil analysis, and real-time farm management. These innovations aid data-driven decision-making, operational automation, and sustainable agricultural expansion by improving monitoring and resource utilization. Large-scale smart farming system installation is difficult despite technology. Existing research suffers from limited datasets, restricted experimental settings, scalability issues, cybersecurity risks, interoperability issues, and expensive computing demands. In connected agricultural ecosystems, data privacy, safe transmission, model interpretability, and real-time validation remain concerns. The literature strongly suggests safe, intelligent, and data-driven agricultural frameworks with AI, IoT, and cybersecurity to increase digital agriculture system efficiency, reliability, and sustainability [4] [5].

Table 1. Gap in industry as per the area and future scope identification

Area	Current Industry Practice	Identified Gap	Impact	Future Opportunity
Agriculture (Biocontrol)	Use of biofertilizers like <i>Bacillus</i> spp.	Inconsistent field performance and formulation issues	Reduced farmer trust and adoption	Development of stable, crop-specific formulations
Precision Agriculture	Use of sensors and ML models for monitoring	Limited scalability and real-time deployment	Inefficient large-scale farming solutions	Integration with edge computing and real-time analytics
Smart Irrigation (IoT)	Automated irrigation systems	Dependence on internet and small-scale testing	Reliability issues in rural areas	Offline-capable and scalable IoT solutions
Cybersecurity (AI Models)	AI-based threat detection systems	High computational cost and lack of real-world validation	Limited deployment in resource-constrained environments	Lightweight and scalable security frameworks
Data Trustworthiness	Use of cryptographic and blockchain systems	Fragmented implementation and lack of standardization	Data security risks	Unified frameworks and post-quantum security
Machine Learning Models	High-accuracy predictive models	Lack of interpretability and overfitting issues	Reduced decision transparency	Development of explainable and robust AI models

2.1 Connection with Existing Theory

Research promotes technology adoption, intelligent decision-making, and secure digital agriculture ideas. TAM best explains agricultural stakeholders' embrace of AI-enabled smart farming technologies. TAM reveals how perceived usefulness and ease of use affect farmers' intentions to utilize IoT-based monitoring systems, AI-driven

crop management tools, blockchain-enabled agricultural platforms, and precision farming apps. In digital agriculture cybersecurity, TAM evaluates how trust, usability, security perception, and technical dependability impact smart farming system and connected agricultural infrastructure adoption [5]. The study supports Data-Driven Decision-Making Theory, which promotes AI and ML for agricultural analytics and farm security. AI and ML models identify patterns, predict risks, optimize resource usage, and automate decision-making using massive agricultural information from IoT devices and smart sensors. These technologies improve crop monitoring, irrigation management, anomaly detection, cybersecurity threat identification, operational efficiency, and sustainability in digital agriculture. Smart farming ecosystems with data-driven analytics and secure agricultural networks are more dependable [6].

3 RESEARCH METHODOLOGY

We reviewed current advances in AI, ML, IoT, and cybersecurity in digital agriculture in a comprehensive literature study and analytical assessment. To identify trends, approaches, problems, and research needs, the study examined smart farming, precision agriculture, AI-enabled monitoring, and secure agricultural systems academic articles. Previous studies were compared to assess implementation methods, operational constraints, and secure and sustainable digital agricultural ecosystem research potential [7].

3.1 Data Collection

Secondary data comes from peer-reviewed journal articles, conference papers, and academic publications on AI, ML, IoT, cybersecurity, and precision agriculture. Research in 2020–2026 included smart farming systems, secure digital agriculture, AI-enabled monitoring, blockchain applications, and intelligent agricultural decision-support technology. Publication selection was based on research relevance, methodological clarity, findings quality, and digital agricultural cybersecurity contribution. A organized tabular review of study goals, methodology, findings, restrictions, and future research directions revealed technical gaps and expanding opportunities in safe smart agricultural systems [8].

3.2 Methodology Used

Researchers used qualitative and comparative methodologies in this investigation. Each selected research article is rigorously assessed for its technique, outcomes, cautions, and future potential. The following steps are followed:

1. Selecting relevant research papers using specified criteria is called "literature screening."
2. Data Extraction: A table organizes each source's key points.

3. Conclusion Based on Results: Various studies indicate that the research environment has several similarities, strengths, and limitations.
4. Interpretation: Fresh insights may lead to new research directions and technical enhancements.

Technology can improve smart systems, cybersecurity, agriculture, and healthcare, according to this study.

4 DATA ANALYSIS AND RESULTS

AI, ML, and IoT are being used in digital agriculture and smart agricultural systems, according to research. For crop monitoring, plant disease detection, yield prediction, soil analysis, and resource management, researchers use deep learning models, CNNs, and hybrid machine learning. AI-enabled IoT systems gather real-time data, monitor farms, and make smart choices to improve operational efficiency and precision agriculture [9]. Many research use simulation-based models, experimental approaches, and data-driven analytical frameworks to study AI-enabled agriculture. Image-based crop phenotyping, pest detection, and plant pathology analysis use deep learning, and ensemble and hybrid ML models improve prediction accuracy and system reliability in varied situations. For sustainable agriculture, AI-driven smart farming systems optimize water, fertilizer, and pesticide usage and forecast climatic and agricultural risk. These developments have not solved dataset quality, scalability, interoperability, cybersecurity risks, or real-world implementation. Literature recommends stronger validation frameworks, explainable AI models, secure IoT infrastructure, and interdisciplinary methodologies that combine agricultural expertise with data science and cybersecurity. Future research will focus on scalable, safe, and environmentally sustainable digital agriculture ecosystems that link theoretical AI models with practical agricultural applications [10].

4.1 Results and Discussion

The findings reveal that AI, ML, and IoT have considerably improved digital farm system efficiency and sustainability. AI-enabled smart farming data-driven decision-making models increase crop monitoring, plant disease detection, irrigation management, yield prediction, and resource optimization. CNNs, Random Forest, and XGBoost surpass statistical techniques in prediction and classification. These technologies enable precision agriculture with real-time monitoring, automated farm management, and advanced agricultural analytics [11]. AI-powered agricultural systems minimize water, fertilizer, and pesticide consumption, and increase environmental monitoring for sustainable farming. Deep learning and IoT frameworks increase climate variability and agricultural risk prediction. Wide-scale adoption is hindered by cybersecurity, real-world validation, scalability, infrastructure, interoperability, and the requirement for large, high-quality information. In farming, environmental unpredictability and high computational costs affect system reliability.

The paper recommends safe and scalable hybrid AI models, explainable AI approaches, durable IoT infrastructure, and improved digital farm cybersecurity. Multidisciplinary collaboration and large-scale field application are needed to create trustworthy, efficient, and sustainable smart agricultural ecosystems [12].

5 CONTRIBUTION TO THE KNOWLEDGE

5.1 Academic Contribution

To improve digital agriculture cybersecurity, this research analyzes how AI, ML, IoT, blockchain, and precision farming technologies are integrated in smart agricultural settings. CNNs, YOLO frameworks, SVMs, Random Forest, and hybrid machine learning increase crop monitoring, plant disease identification, predictive analytics, irrigation control, and resource optimization, according to research. These technologies improve data-driven decision-making and smart agriculture. The study emphasizes blockchain-enabled data management, dependable IoT connections, and cybersecurity-aware smart farming frameworks for secure agricultural infrastructures. It identifies research needs in digital agriculture system scalability, interoperability, data safety, explainable AI, and real-world deployment. Using AI-enabled agricultural analytics and cybersecurity, the study encourages rigorous, transparent, and secure smart farming ecosystem research. The findings also spur interdisciplinary agricultural science, cybersecurity, and intelligent data analytics research to develop scalable and sustainable digital agriculture solutions [13,14].

5.2 Industry Contribution

The article stresses AI, ML, IoT, and blockchain in safe and sustainable digital agricultural systems, making substantial industry advances. Agriculture enterprises may improve crop yield, irrigation efficiency, pesticide and fertilizer usage, and farm management using AI-enabled smart farming solutions. AI-driven plant disease detection models, predictive analytics, IoT-based monitoring systems, and automated decision-support systems enable precision farming and real-time agricultural monitoring. Blockchain and secure data management improve agricultural supply chain transparency, traceability, and cybersecurity. These technologies protect agricultural data, connect farming equipment, and build digital agriculture ecosystem trust. Data-driven decision-making using AI-driven prediction models helps agricultural companies manage climate risks, resource allocation, and operational unpredictability. The report recommends scalable and strong smart agricultural infrastructure for sustainability, operational efficiency, and food security. The findings will assist agribusinesses, agricultural technology providers, policymakers, and precision farmers seeking secure, intelligent, and automated agricultural solutions for future digital farming [15].

5.3 Policy Suggestions to the Domain

Many safe and sustainable digital farm policy suggestions are supported by these findings. AI, IoT, blockchain, and precision farming should be supported by government and agricultural research funding, innovation programs, and financial incentives. Policy frameworks should support safe smart farming infrastructure, cybersecurity, data privacy, interoperability, and ethical AI-enabled agricultural technology use. Regulatory bodies should standardize safe agricultural data management, IoT communication protocols, and blockchain-based traceability systems to improve digital agriculture ecosystem trust and reliability. Large-scale precision agriculture needs rural internet, cloud, and smart sensor infrastructure. The study emphasizes farmer training, digital literacy, and capacity-building to enhance agricultural stakeholder technology adoption. Small and marginal farmers may benefit from subsidies and financial aid for smart agriculture technologies. Academic institutions, agribusinesses, technology providers, and government agencies must work more to promote long-term innovation, sustainable agriculture, and resilient digital farming ecosystems [16,17].

6 SUGGESTED FRAMEWORK FOR THE INDUSTRY

Agriculture and associated enterprises can integrate new technology more easily with a multi-tiered and interconnected architecture. After reviewing the pertinent data, the framework was created.

1. **Data Acquisition Layer:** This layer collects real-time, high-quality data from smart devices, drones, satellite pictures, and IoT sensors. We regularly monitor soil moisture, crop health, nutrient levels, temperature, and humidity. Such factors include. Data enables precision agriculture and educated judgments.
2. **Data Management & Security Layer:** Block chain and cloud computing are recommended for data processing and storage to maintain security. Anomaly detection, secure transmission methods, and enhanced encryption help digital farm systems overcome issues. These processes guarantee data source reliability, privacy, and integrity.
3. **Analytics & Intelligence Layer:** This layer uses deep learning, machine learning, and AI models to improve agricultural decision-making. Examples include Random Forest, CNNs, and reinforcement learning. Advanced algorithms assess risks, forecast harvests, distribute resources, and discover food-related diseases. Microbiome and omics-based analytics improve diagnosis, enable sustainable agriculture, boost productivity, and reduce environmental impact. Integration inevitably leads to this.
4. **Application Layer (Smart Farming Solutions):** Industry analytics have created climate-smart agricultural solutions, labour assistance technology like exoskeletons and robotics, intelligent irrigation systems that optimize water use, and AI-based crop disease monitoring and detection tools. This layer increases agricultural lifetime, efficacy, and harvest via data-driven insights.
5. **Decision Support System (DSS):** A Decision Support System provides useful information and advice to agribusinesses and farmers. Multiple datasets help data-driven

decision-making and early disease and pest alerts. We can boost output and reduce environmental effect by regulating water, fertilizer, and labour.

6. **User Interface & Accessibility Layer:** This layer speeds regional language, web dashboard, and mobile app support. Making user interfaces adaptable and easy to use improves usability. This ensures meaningful suggestions and information for stakeholders, including farmers. This means farmers without tech skills may interpret and use complex data.
7. **Sustainability & Feedback Layer:** Tracking and reporting are the only ways to improve system performance. AI algorithms get new data, measure environmental impacts, and record agricultural productivity. By preserving the system's efficiency, sensitivity to changing agricultural circumstances, and precision, this adaptive technology permits perfect farming throughout time.
8. **Policy & Integration Layer:** If an organization seeks widespread support, obey the guidelines. These requirements may be met by bio-based and AI frameworks. Stronger public-private collaborations are needed to accelerate research, pool resources, and support novel agriculture solutions.

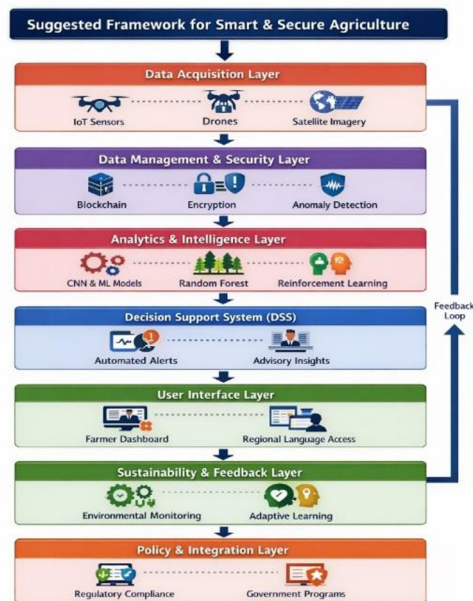


Fig. 1. Proposed Multi-Layered Hybrid AI Framework for Smart and Secure Digital Agriculture

The suggested multi-layered smart farming architecture uses AI, IoT, blockchain, and data-driven decision-support mechanisms to develop safe, intelligent, and sustainable digital agricultural systems. Real-time agricultural monitoring, secure data management, predictive analytics,

and automated farm operations boost production and reduce resource waste and environmental impact. IoT sensors and smart devices gather data, blockchain and cloud platforms safeguard it, AI-powered analytics monitor crops and detect illnesses, intelligent decision-support systems make choices, and farmers and agricultural stakeholders utilize the interfaces. Smart farming flexibility, scalability, and operational resilience are enhanced by cybersecurity, sustainability, and feedback. Through secure connection, intelligent automation, and real-time agricultural analytics, the platform provides trustworthy and scalable digital agriculture ecosystems that can address future agricultural and cybersecurity issues [18].

7 CONCLUSION

This study explains how AI, ML, IoT, and blockchain are changing digital and smart agriculture. AI-enabled precision farming, intelligent irrigation, crop disease detection, predictive analytics, and automated monitoring increase agricultural productivity, efficiency, and resource management. YOLO, CNNs, and hybrid machine learning models increase smart agricultural systems and real-time decision-making. According to the research, related agricultural issues are requiring stronger cybersecurity. Cloud platforms, blockchain-based data management systems, and IoT devices pose data privacy, secure communication, scalability, interoperability, and system reliability challenges. Constrained datasets, computational complexity, explainable AI, and lack of real-world validation prevent large-scale safe digital agriculture framework implementation. The hybrid AI-based framework creates reliable, scalable, and lasting smart agricultural ecosystems via secure data management, AI-driven analytics, and intelligent decision-support mechanisms. Future research should increase cybersecurity infrastructure, scalable AI models, real-time deployment, and interdisciplinary collaboration for safe and sustainable digital farm systems.

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