A Review on Advancing Technologies in Precision Agriculture: Applications, Challenges, and the Way Forward

Article *in* Procedia Computer Science · January 2025

DOI: 10.1016/j.procs.2025.07.221

Okurwoth Vicus Ocama
Makerere University

Witesyavwirwa Vianney Kambale
Alpen-Adria-Universität Klagenfurt

Tasho Tashev
Technical University of Sofia

Kyandoghere Kyamakya
Alpen-Adria-Universität Klagenfurt

Available online at www.sciencedirect.com

ScienceDirect

Procedia Computer Science 265 (2025) 572–577

Procedia Computer Science

www.elsevier.com/locate/procedia

12th International Symposium on Emerging Inter-networks, Communication and Mobility
August 4-6, 2025, Leuven, Belgium

A Review on Advancing Technologies in Precision Agriculture: Applications, Challenges, and the Way Forward

Okurwoth V. Ocama[a], Yves-Christophane N. Medagbe[a], Sarah Akello[b], Witesyavwirwa V. Kambale[d], Tasho Tashev[c], Kyandoghere Kyamakya[d], Selain K. Kasereka[a,c,e,*]

[a]*Department of Mathematics, Statistics and Computer Science, University of Kinshasa, 190 Kinshasa XI, DR. Congo*
[b]*College of Agriculture and Environmental Sciences, Makerere University, Kampala-Uganda*
[c]*Department of Information Measurement Systems, Technical University of Sofia, Sofia, Bulgaria*
[d]*Institute of Smart Systems Technologies, University of Klagenfurt, Klagenfurt, Austria*
[e]*ABIL Research Center, 190 Kinshasa XI, DR. Congo*

Abstract

Whereas the global population is expanding, there is a need to increase agricultural production to meet the demands of the current generation without compromising on conserving the environment. Smart agriculture presents an opportunity as an advanced technique that uses cutting-edge technology and data analysis to address such challenges. The integration of these technologies in farming has increased crop yields and boosted production. This review delves into emerging agricultural technologies including Artificial Intelligence (AI), Internet of Things, Cloud computing, Big data and Blockchain technology among others. The paper focuses on their applications in the agrarian industry. Multiple reviews of articles highlighted state-of-the-art innovations like precision fertilization, automated irrigation, real-time crop monitoring systems, and disease detection systems. As farmers are encouraged to embrace these technologies, limiting factors like costs, data, and privacy concerns need to be clearly articulated. Therefore, future directions for the full adoption of these cutting-edge technologies are highly recommended.

Keywords: Smart Agriculture, Internet of Things (IoT), Machine Learning (ML), Precision Agriculture, Big data, Cloud computing, and Blockchain technology.

1. Introduction

The agrarian industry is of highly significant to the global economy. This industry serves as the backbone of food security and livelihoods for the world's population. By 2050, the human population is expected to reach 10 billion

* Corresponding author. Tel.: +243-821-828-964.
E-mail address: selain.kasereka@unikin.ac.cd

10.1016/j.procs.2025.07.221

people, and this therefore means an increase in precision agriculture for contemporary agrarian research [16]. This calls for an urgent need to increase food production to meet the demand of the growing populace. In many regions, particularly in Africa, the reliance on traditional farming methods and natural rainfall for agricultural production exacerbates the vulnerability of agri-food systems to climate variability. A majority of African countries rely on rainfed agriculture [13]. This dependency is a threat to food security, hinders economic development, and thus exacerbates poverty in rural communities mainly due to unpredictable rainfall and uncertainty in its patterns due to climate change. A notable increase in crop yield, reduced costs, improved efficiency and minimal environmental impacts have been registered from the introduction of Precision agriculture. New technologies like sensors, AI, GPS mapping and automation are helpful in monitoring crops fields for efficiency [10]. The African continent is adopting an innovative approach to farming, together with the development of appropriate technologies that can support precision farming in order to guarantee food security. The need for affordable, high-quality food, its security and the alarming growing population has prompted the agricultural industry to gradually incorporate technology into farming operations [24].

This review presents a range of advancing technologies and their pivotal role in precision agriculture. It highlights opportunities, challenges, and future perspectives they present. These include Artificial Intelligence (AI), Machine Learning (ML), IoT, Big data analytics, cloud computing and Blockchain technology [22]. ML, a subset of AI, uses computational methods to analyze data and recognize patterns. ML uses experience to make accurate decisions [22]. ML is being applied in crop yield prediction, crop disease detection and weed detection etc. In recent years, the components of IoT have been integrated into precision agriculture for increased food production [1]. These technologies are essential because they support real-time monitoring of crop health, soil conditions, weather and automation processes like fertilizer administration and irrigation. Combining these IoT components in precision agriculture results in increased efficiency, productivity and agricultural sustainability. The component of Blockchain technology ensures transparency and traceability of the agricultural supply chain, enabling farmers to store and share data with agribusinesses and researchers [4]. On the other hand, Cloud computing enables real-time data processing, i.e. processing information from sensors, drones, and satellites to generate insights on soil health, crop performance, and weather patterns as well as facilitating remote farm management. Additionally, Big data technology enables predictive modelling and data-driven decision-making in farm management [3].

All these technological advancements have created a big shift from the reliance on traditional farming methods and natural rainfall for agricultural production to modern farming to achieve efficient resource utilization.

The paper is structured as follows: Section 2 outlines the methodology employed in this review. Section 3 discusses key applications of advancing technologies. Section 4 examines challenges hindering technological progress in agriculture. In Section 5, we explore future directions and visions for technological advancements within the agricultural domain. Finally, Section 6 concludes the study.

2. Research Methodology

The study adopted a systematic literature review methodology that follows the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework, therefore ensuring transparency, reproducibility, and rigor in the study selection. Our review focused on precision agriculture technologies such as AI, ML, IoT, Blockchain, Big Data, and Cloud Computing. We comprehensively searched across several academic databases. Among the platforms are: Google Scholar, ScienceDirect, ResearchGate, IEEE Xplore, arXiv, and MDPI. We employed a Boolean keyword search in order to obtained only relevant academic studies for our paper. We then refined the search with terms like ”Artificial Intelligence AND Agriculture”, ”Machine Learning + Smart Farming”, and “Agriculture in Africa AND Technology.” We also restricted our research to publications from 2020 to 2025 to prioritize recent advancements. Initially, over 168 papers were identified across the different databases, but after using a reference management software, that is Zotero, we removed 42 duplicates. The remaining 126 studies underwent title and abstract screening, resulting in the exclusion of 39 irrelevant papers. We assessed the eligibility of the remaining 87 full-text articles. We used peer-reviewed emperical studies with focus on precision agriculture technologies. Studies lacking technical depth, peer review, or empirical data were excluded. This left 42 high-quality studies for final synthesis. Data extraction was based on the technology types and applications in precision agriculture, the challenges of adopting and applying these technologies and the future perspectives regarding the adoption and use of these technologies. We obtained information on soil health monitoring, crop yield prediction, pest and disease detection, as well as climate adaptation strategies like irrigation systems. This was to enhance their potential for productivity and sustainability.

3. Application of Different Technological Systems in Smart Agriculture

In recent years, there has been an increasing trend of technological development in the agrarian industry. Advanced technologies like AI are being used to improve and address the challenges of agricultural productivity. AI and other technologies like IoT are being employed to choose suitable crop types for planting, pest and disease management, yield prediction, weed detection, fertilizer application and forecasting crop production [9]. These new technologies are characterized by data-driven management, sustainable agricultural production, efficient resource optimization and minimal environmental impact [10]. AI and ML models such as Support Vector Machine, and Artificial Neural Network analyze vast datasets to provide predictive insights. Elaborative information on the emerging technologies, their models and applications in precision agriculture are illustrated in Figure 1.

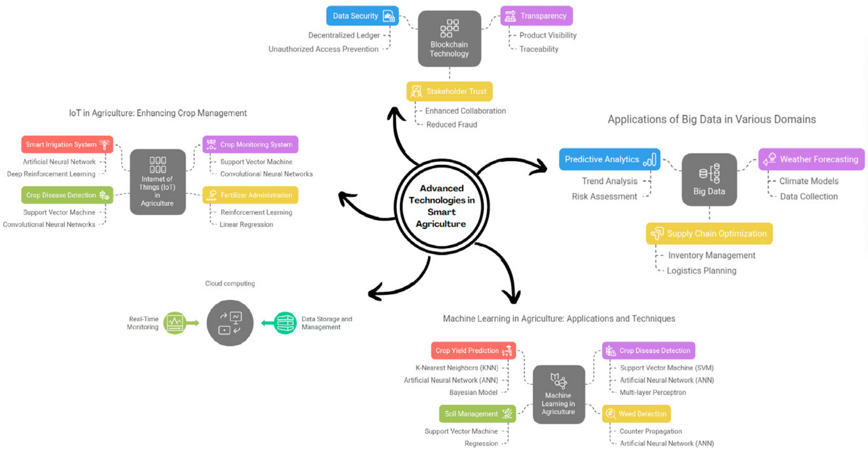

Fig. 1. Taxonomy of advance technologies in Smart Agriculture.

3.1. *Internet of Things (IoT)*

IoT is a cutting-edge technology that involves connecting network hardware devices and software that can collect, exchange and process data without human intervention [8]. Advanced IoT components like Biodegradable soil and leaf sensors, smart nano drones, microclimate stations, and Edge AI chips are being used in precision agriculture for measuring plant stress, soil moisture, enabling hyper-local forecasts by farmers, and applying micro-doses of pesticides to plants. This results in increased efficiency, productivity and agricultural sustainability. With the development of powerful sensors, IoT is being used widely in precision agriculture for smart irrigation, fertilizer administration, and crop monitoring.

Smart Irrigation System: IoT component like the Aiper IrriSense Smart Sprinkler offers precise watering and reduces water usage. This irrigation system is a smart sprinkler system that does not require buried pipes or additional hardware. The Advanced soil sensors with Ion-Selective Electrodes (ISEs) provide real-time and location-specific soil data, which optimizes the irrigation schedule. The National Science Foundation (NSF) invented a powerful IoT component called Biodegradable soil and leaf sensors, which measure soil moisture and nutrient levels. These sensors dissolve naturally after the season, leaving behind zero environmental impact [25]. The ESP32-Based Irrigation controller uses the integrated ESP32 microcontroller with various sensors used for monitoring climatic conditions. This leads to automated irrigation.

Crop Monitoring System: Several powerful IoT components are transforming crop monitoring systems and precision agriculture. The use of colorimetric leaf sensors with robotic monitoring has enabled real-time monitoring of plant health, which has enabled timely interventions [7]. Hyperspectral imaging drones are being used to detect crop diseases, nutrient deficiencies and invasive species. The GroGuru Advanced soil sensors probes detect moisture, salinity and temperature. This, in turn, offers invaluable information about soil health and subsequent crop health monitoring. The goal of these innovations is to improve real-time data collection, conserve resources and promote sustainable agriculture practices.

Fertilizer Administration:Embedded IoT components are used to apply fertilizer in the right amount, at the right time for healthy crop growth. The data collected by the sensors enables the precision application of fertilizers to crops. Farmers use NPK sensors to monitor soil nutrients, thus enabling fertilizer administration when needed [17]. Precision fertilizer application enables resource efficiency and reduced ecological impact. In some articles, Wireless Sensor Networks were used to collect and analyze sensed data. This system was for a greenhouse and was set up to monitor fertilizer application, pests, irrigation, and climate variability.

3.2. Machine Learning

ML is one of the branches of AI. ML allows computers to make decisions based on trained data without explicitly programming them. Models like Decision Tree, SVM, and CNN use large datasets to automate complex tasks, as they identify patterns and improve performance over time. In agriculture, ML algorithms are useful for designing systems that are vital for crop selection, automatic irrigation systems, fertilizer recommendation and weeding. Thus, labor costs are decreased while productivity and efficiency are increased.

Crop Yield Prediction:The ML models use datasets to forecast crop yields and give precise estimates [6]. Deep MMCropYNet which is a deep learning based multimodal crop yield prediction network that integrate time series and image data. This improves the ability to learn to significant features from complex data, leading to more accurate crop yield prediction. The Federated Learning for Agriculture, known as FL-AGRN is a federated learning model that enables collaborative training of ML models across multiple devices. This facilitates development of robust crop yield prediction models while ensuring data privacy and security [19]. In the article [6], the authors designed different models to predict potato crops. After experimenting, they found out that Graph Neural Networks and Long Short Term Neural Networks have great precision. Also, at the same time, it captures intricate temporal and spatial patterns that are present in the data. These innovative ML models are significantly advancing crop yield prediction capabilities. Thus, leading to more informed decision-making, optimized resource utilization, and sustainable agricultural practices.

Crop Disease Detection:The African Centre of Excellence in Internet of Things (ACEIoT) carried out a reserach at the University of Rwanda (UR) known as the The MobilePlant ViT. This is a lightweight Hybrid Transformer (ViT) designed for mobile-friendly plant disease detection [23]. This model enables real-time, on-field disease detection. This enables timely intervention of farmers to manage their crops. The E-Farm AI, developed in Senegal, integrates ensemble ML models with MobileNet for disease classification. This assists farmers with effective disease management strategies. Table 1 below summarizes some research studies conducted on disease detection using ML models

Table 1. Summary of the review paper about Disease detection.

References	Crops	Identified features/Testing area	Models	Best output
J. Kaur et al. 2024 [11]	Wheat	Septoria leaf blotch and Soya bean rust	Convolutional-Neural Networks	Accuracy = 98%)
R. Cristin et al. 2020 [5]	Various crops	Used RGB (Red, Green, and Blue) images to classify infected leaves	Rider-CSA Based DBN (Deep Belief Network)	Accuracy = 0.877 Sensitivity = 0.862 Specificity = 0.826
G. Sambasivam et al. 2021 [21]	Cassava	Used 10,000 labelled images from Kaggle for 5 cassava leaf disease categories	Convolutional Neural Networks	Best Acc. = 99.30% lowest Acc. = 76.9%

Weed Detection and Soil Management: ML models have been designed and used to capture images of plants. But also to recognize patterns to classify plants as crops [2]. For instance, Support Vector Machines are being used to classify crops from weeds based on the shapes and texture of the plants. Convolutional Neural Networks are being used to extract complex features from the captured images. The model, EcoWeedNet, was designed for sustainable, low-carbon weed detection. As stated in the research, the model supports sustainable agriculture by reducing energy consumption and enabling real-time weed detection on resource-constrained devices [12]. Advanced technologies are being used in soil management practices such as AI-enabled soil Health management tools. These technologies collect data on soil characteristics and then analyse them using ML models. This enables farmers to make informed decisions on farm operations, thus resulting in increased soil health, sustainable agriculture and minimum environmental impacts.

3.3. Cloud Computing and Big Data Technology

Cloud computing, most commonly referred to as "Cloud", is a leading-edge technology that has transformed the agricultural industry. Cloud computing has reinforced precision agriculture by offering scalable storage and processing capabilities for large agricultural datasets [15]. Recently, cloud computing has facilitated real-time data collection and analysis of vast agricultural data from IoT devices, drones and satellites. This has enabled real-time monitoring and decision making. Agricultural Data is collected and stored in the database by drones, sensors, and smartphones. After modeling, this data is analyzed to make informed agricultural decisions such as crop yield prediction, disease outbreaks etc. This has facilitated the efficient use of resources, reduced costs, enhanced yields and enabled farmers to predict future market prices [26]. Big Data is being used to analyze market and pricing trends, therefore enabling farmers to make informed decisions.

3.4. Blockchain Technology

Recently, Blockchain technology has become a focus for researchers and agriculturalists. This robust technology is transforming agriculture in its diverse capabilities. In blockchain, data and transactions that are related to farming can be securely stored and verified in a decentralized ledger [20]. Blockchain offers an element of traceability where an agricultural product is tracked in real-time from the farm to the consumer. There is also a property of smart contracts, where payment between a farmer and a buyer is automated. In the article [14], the AgriFLChain framework combines blockchain with federated learning to enable privacy-preserving and trustworthy crop yield prediction.

4. Challenges to Adopting the Advancing Technologies in Precision Agriculture

Most of these technologies are in their formative stage. Although they are positively transforming the agricultural sector, their full integration into farming is a challenge to most farmers. IoT devices like sensors, drones, and robotics are very expensive to purchase and implement. Most farmers find difficulty in using it because of its high initial cost. These technologies are advanced and need experts to operate, which is still a problem for most farmers [10]. There is a challenge of limited internet connectivity, especially in rural areas. This is because the government does not prioritize constructing IT infrastructure in remote areas, which is crucial for data transmission and cloud-based solutions. With the inception of cutting-edge technologies, agriculturalists have expressed concerns over data security and privacy [8]. These concerns have limited the full integration of these technologies into farming. Finally, these technologies require high maintenance costs. This regular maintenance might be a problem for rural farmers, hence limiting the integration of advanced technologies into farming.

5. Future Perspectives and Opportunities

More areas demand research for the complete integration of technologies into farming as we travel towards smart agriculture. Frameworks emphasizing low-cost, open-source solutions are being suggested to support sustainable agriculture in underdeveloped areas in resource-constrained surroundings [18]. Agrivoltaics provides a two-fold advantage by combining photovoltaic systems with agriculture: crop production and generation of renewable energy. This approach can improve land-use efficiency and provide additional income streams for farmers. As AI, big data analytics and IoT get integrated into agriculture, the need for protecting the sensitive information of stakeholders will arise. More research efforts should be on advanced encryption techniques to curb security concerns. There is anticipation of increased investments in agri-tech startups and improved food security.

6. Concluding Remarks

Several studies indicate that the global population is growing, and this means an increase in agricultural foods. For so long, agricultural production has been entirely dependent on unpredictable rainfall. To ensure the supply of food meets the escalating demands, farmers need to embrace innovative technologies as a method of farming. This review focuses on technologies being used to revolutionize agriculture, including automated irrigation systems among others. The smart irrigation supplies water to crops at the time of need, hence has promoted sustainable agricultural production. The article also reviewed some of the barriers hindering adoption of the innovative technologies. However, other research recommended that with the support of the government, prices of IoT equipment could be subsidized.

Agro-farmers could be trained and have reliable internet connections in remote areas. In agriculture, state-of-the-art technologies are still in the infancy stage, therefore an in-depth inquiry is encouraged in the field to elevate the pace of adoption and use in the agricultural sector.

Acknowledgments

This work has been realized with financial support by the European Regional Development Fund within the Operational Programme "Bulgarian national recovery and resilience plan", Procedure for direct provision of grants "Establishing of a network of research higher education institutions in Bulgaria", under the Project BG-RRP-2.004-0005 "Improving the research capacity and quality to achieve international recognition and resilience of TU-Sofia".

References

[1] N. Abu, W. M. B. Wan Daud, C. Ong, A. Kassim, T. Izzuddin, M. Sukhaimie, M. Norasikin, and A. Rasid. Internet of things applications in precision agriculture: A review. *Journal of Robotics and Control (JRC)*, 3:338–347, 05 2022.

[2] L. Benos, A. C. Tagarakis, G. Dolias, R. Berruto, D. Kateris, and D. Bochtis. Machine learning in agriculture: A comprehensive updated review. *Sensors*, 21(11), 2021.

[3] S. A. Bhat and N.-F. Huang. Big data and ai revolution in precision agriculture: Survey and challenges. *IEEE Access*, 9:110209–110222, 2021.

[4] R. Chaganti, V. Varadarajan, V. S. Gorantla, T. R. Gadekallu, and V. Ravi. Blockchain-based cloud-enabled security monitoring using internet of things in smart agriculture. *Future Internet*, 14(9), 2022.

[5] R. Cristin, B. S. Kumar, C. Priya, and K. Karthick. Deep neural network based rider-cuckoo search algorithm for plant disease detection. *Artificial intelligence review*, 53:4993–5018, 2020.

[6] E.-S. El-kenawy, A. Alhussan, N. Khodadadi, S. Mirjalili, and M. Eid. Predicting potato crop yield with machine learning and deep learning for sustainable agriculture. *Potato Research*, 07 2024.

[7] M. Hopkins, A. K. Li, S. Kramadhati, J. Arnold, A. Mallavarapu, C. Lawrence, V. Murali, S. J. Koppal, C. Kagan, and V. Kumar. Robotic monitoring of colorimetric leaf sensors for precision agriculture, 2025.

[8] G. Idoje, T. Dagiuklas, and M. Iqbal. Survey for smart farming technologies: Challenges and issues. *Computers Electrical Engineering*, 92:107104, 2021.

[9] M. Javaid, A. Haleem, I. H. Khan, and R. Suman. Understanding the potential applications of artificial intelligence in agriculture sector. *Advanced Agrochem*, 2(1):15–30, 2023.

[10] E. M. B. M. Karunathilake, A. T. Le, S. Heo, Y. S. Chung, and S. Mansoor. The path to smart farming: Innovations and opportunities in precision agriculture. *Agriculture*, 13(8), 2023.

[11] J. Kaur, A. Choppadandi, P. K. Chenchala, S. Nuguri, and R. Saoji. Machine learning-driven iot systems for precision agriculture: Enhancing decision-making and efficiency. pages 1735–188, 12 2024.

[12] O. H. Khater, A. J. Siddiqui, and M. S. Hossain. Ecoweednet: A lightweight and automated weed detection method for sustainable next-generation agricultural consumer electronics. *arXiv preprint arXiv:2502.00205*, 2025.

[13] C. Lontsi Saadio, H. Adoni, R. Aworka, J. Zoueu, F. Kalala Mutombo, and C. Mberi Kimpolo. Crops yield prediction based on machine learning models: Case of west african countries. *SSRN Electronic Journal*, 01 2022.

[14] T. Manoj, K. Makkithaya, and V. Narendra. A blockchain-assisted trusted federated learning for smart agriculture. *SN Computer Science*, 6(3):221, 2025.

[15] J. Miller and S. Shekhar. Cloud computing in smart agriculture: Data storage, processing, and analysis. 05 2024.

[16] A. Monteiro, S. Santos, and P. Gonçalves. Precision agriculture for crop and livestock farming—brief review. *Animals*, 11(8), 2021.

[17] A. Morchid, R. El Alami, A. Raezah, and Y. Sabbar. Applications of internet of things (iot) and sensors technology to increase food security and agricultural sustainability: Benefits and challenges. *Ain Shams Engineering Journal*, 15, 10 2023.

[18] M. Nawaz and M. I. K. Babar. Iot and ai for smart agriculture in resource-constrained environments: challenges, opportunities and solutions. *Discover internet of things*, 5(1):24, 2025.

[19] U. Nirosha and G. Vennila. Enhancing crop yield prediction for agriculture productivity using federated learning integrating with graph and recurrent neural networks model. *Expert Systems with Applications*, page 128312, 2025.

[20] T. H. Pranto, A. A. Noman, A. Mahmud, and A. B. Haque. Blockchain and smart contract for iot enabled smart agriculture. *PeerJ Computer Science*, 7:e407, 2021.

[21] G. Sambasivam and G. D. Opiyo. A predictive machine learning application in agriculture: Cassava disease detection and classification with imbalanced dataset using convolutional neural networks. *Egyptian Informatics Journal*, 22(1):27–34, 2021.

[22] R. Sharma, S. S. Kamble, A. Gunasekaran, V. Kumar, and A. Kumar. A systematic literature review on machine learning applications for sustainable agriculture supply chain performance. *Computers Operations Research*, 119:104926, 2020.

[23] M. R. Tonmoy, M. M. Hossain, N. Dey, and M. Mridha. Mobileplantvit: A mobile-friendly hybrid vit for generalized plant disease image classification. *arXiv preprint arXiv:2503.16628*, 2025.

[24] S. Twetwa-Dube and O. Oki. Technology adoption for precision agriculture in africa: a bibliometric analysis. pages 1–7, 07 2023.

[25] A.-M. Zaccarin, G. M. Iyer, R. H. Olsson, and K. T. Turner. Fabrication and characterization of soil moisture sensors on a biodegradable, cellulose-based substrate. *IEEE Sensors Journal*, 24(6):7235–7243, 2023.

[26] Y. Zhang. Application of big data in smart agriculture. *Advances in Resources Research*, 4(2):221–230, 2024.