



RESEARCH PAPER

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Design and architecture of an IoT-enabled bamboo resource management system: Data-driven approach for sustainable agriculture

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ABSTRACT

Bamboo is an important renewable resource with significant ecological and economic value, particularly in regions where it contributes to rural livelihoods and sustainable agriculture. However, traditional bamboo farming practices often rely on manual monitoring and limited data, which can reduce efficiency in resource management and crop productivity. This study proposes the design and architecture of an Internet of Things (IoT)-enabled Bamboo Resource Management System (BRMS) aimed at supporting sustainable bamboo cultivation in Northeastern Cagayan, Philippines. The system was developed using a design-oriented research approach that integrates stakeholder feedback, field observations, and analysis of existing bamboo farming challenges. The proposed framework consists of four main stages: requirement identification, system architecture design, hardware and software selection, and development of a comprehensive data model. The system utilizes IoT sensors and GPS technology to collect real-time environmental and spatial data from bamboo plantations. These data are transmitted through cellular and Wi-Fi networks and stored in a cloud-based MySQL database. Data analysis is conducted using Python-based analytical libraries to generate actionable insights for resource management. A web-based dashboard developed using PHP, JavaScript, and Bootstrap enables users to monitor plantation conditions and access decision-support information through an interactive interface. The proposed BRMS architecture demonstrates how IoT technology and data analytics can improve monitoring, resource allocation, and decision-making in bamboo farming. The system provides a scalable framework for integrating digital technologies into sustainable agricultural practices and may serve as a model for smart farming applications in other crop production systems.

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## INTRODUCTION

Bamboo is a renewable and rapidly growing resource and has many uses in construction, furniture and home goods, such as chopsticks. According to the Department of Science and Technology (DOST), the Philippines is the world's sixth largest exporter of bamboo. Bamboo covers between 39,000 and 53,000 hectares in the country, producing about 36 million culms each year. It suggests the necessity of balancing economic development with environmental concern in the bamboo industry. Bamboo, in the Cagayan Valley, is regarded as both a natural resource and an important part of the local economy. Programs are directed mainly towards building bamboo businesses and to increase farmers' earnings, with seedling production within their own communities as a start. As the need for sustainable practices grows, Cagayan Valley has focused on agriculture modernization. The NEDA Region 2 Research and Development Agenda for 2023-2028 highlights the adoption of smart agriculture practices. These projects focus on better management and using new technology to improve the efficiency of the Agriculture, Forestry, and Fisheries sectors. Technology use among small farmers in the region has grown by 10% each year from 2017 to 2022, showing a strong commitment to digital agriculture and modernization.

Cagayan State University is a pioneer of agricultural innovation with its program on agroforestry through bamboo. It is formulating definite plans, aims, and priorities. The university conducts lots of research and development on bamboo. CSU-Gonzaga is now a significant producer of propagules of bamboo in its area and is also promoting the establishment of bamboo plantations. In its significant partnership, CSU-Gonzaga joined forces with the DENR and with the Cagayan Provincial Environment Natural Resource Office. The partnership is planning to produce 82,500 pieces of bamboo propagules for special purposes such as establishing bamboo plantations and addressing food security that would create new income streams for various communities in the region of Cagayan.

Internet of Things (IoT) technology has increasingly applied itself to agriculture, providing new methods of monitoring and control of resources. The acquisition of masses of real-time data is affected through IoT sensors such as GPS that give us insights into various things like the condition of the environment, the condition of plant life, as well as usage of resources.

Smart systems that combine IoT and data analytics are now able to handle the division of things fairly up to a certain point. They perform problem-solving functions and simultaneously giving recommendations to the people. In the case of bamboo, the temperature, moisture, and soil are monitored continuously by the IoT devices, thus facilitating the perfect care for bamboo.

Research shows strong support for using IoT technology in agriculture. It helps increase yields from the same land while using fewer resources. Dhanaraju *et al.* (2022) call IoT the backbone of precision farming, noting that data improves irrigation and plant care. Gupta *et al.* (2023) found that IoT can detect plant diseases early, reducing crop loss and improving harvests. Overall, studies agree that IoT is essential for modern farming, including bamboo management.

Despite the growing body of research on IoT-based smart agriculture, most existing studies focus on general crop monitoring, irrigation control, or disease detection in major crops such as rice, wheat, and vegetables. Very limited research has explored the application of IoT technologies specifically for bamboo plantation management. Bamboo cultivation requires continuous monitoring of environmental parameters such as soil moisture, temperature, and spatial distribution of plantations, yet traditional management practices still rely largely on manual observation and fragmented data sources. As a result, farmers often lack timely information to support efficient resource allocation and sustainable plantation management. Therefore, there remains a need for a

dedicated IoT-based system that integrates real-time environmental monitoring, spatial tracking, and data analytics to support decision-making in bamboo farming.

Such a bamboo plantation system, using the IoT and data analytics, is envisioned in this paper to realize big bamboo. These will include sensors for data collection in real-time, a master for storage and processing of the data, and a monitor for data display to support decision-making. The new IoT-based and smart data-support model in the area of bamboo adopted herein is intended to overcome the problems of the old bamboo care methods in order to promote eco-friendly farming using the IoT technology and smart data.

## MATERIALS AND METHODS

This study follows the Design Science Research (DSR) methodology, which is commonly applied in information systems and engineering research to develop innovative technological solutions to practical problems. The DSR approach emphasizes the systematic design, development, and evaluation of artifacts such as models, frameworks, or systems intended to address real-world challenges. In this study, the methodology focuses on designing an IoT-enabled Bamboo Resource Management System (BRMS) that supports sustainable bamboo cultivation through real-time monitoring and data-driven decision making.

The development of the proposed system architecture was guided by field observations, stakeholder consultations, and a review of existing literature on smart agriculture and IoT applications in crop monitoring. Traditional bamboo plantation management often relies on manual monitoring and fragmented information sources, which can limit timely decision-making and efficient resource allocation. Therefore, the proposed BRMS integrates sensor-based environmental monitoring, data transmission technologies, cloud-based storage, and analytical tools to provide a comprehensive platform for managing bamboo resources.

The system was developed through four major phases: requirement identification, system architecture design, technical specification and component selection, and data model development. Each phase contributes to building an integrated system capable of collecting, transmitting, analyzing, and visualizing environmental and spatial data relevant to bamboo plantation management.

### Requirement identification

The first phase focused on identifying the functional and technical requirements of the system. Information was gathered from field observations of bamboo plantations, consultations with agricultural practitioners, and a review of smart agriculture technologies. Key requirements included real-time monitoring of environmental conditions, spatial tracking of bamboo plantations, secure data storage, and an accessible platform for visualizing information and supporting management decisions.

### System architecture design

Based on the identified requirements, a conceptual architecture of the Bamboo Resource Management System was developed. The architecture consists of interconnected layers responsible for data collection, communication, processing, and user interaction. IoT sensors deployed in bamboo fields collect environmental data such as temperature, humidity, and soil moisture. GPS modules are used to track the geographic location of bamboo resources. These components form the data acquisition layer of the system.

### Technical specification and component selection

In the third phase, appropriate hardware and software technologies were selected to support system implementation. Environmental sensors are used to measure soil moisture, temperature, and humidity conditions within bamboo plantations. The Arduino Opla IoT Kit and MKR GSM 1400 module provide the platform for sensor integration and wireless communication. Data transmission is achieved through cellular networks and Wi-Fi connectivity,

ensuring reliable communication between field devices and the central system.

For data storage and management, a cloud-based MySQL database was selected due to its reliability and scalability in handling large volumes of sensor data. Data analysis and processing are conducted using Python-based analytical libraries, which enable trend detection, predictive analysis, and data-driven insights. A web-based dashboard developed using PHP, JavaScript, Bootstrap, HTML, and CSS provides an interactive interface for users to monitor plantation conditions and access analytical outputs.

### Data model development

The final phase involved the development of a comprehensive data model that organizes and manages the information collected by the system. The data model includes several core components, such as temperature data, humidity data, soil moisture data, GPS location data, user information, and analytical results. These components enable real-time monitoring of environmental conditions and support data-driven decision-making for bamboo resource management.

By integrating IoT sensors, communication technologies, cloud storage, and analytical tools within a unified framework, the proposed methodology establishes the foundation for a smart bamboo management system capable of improving monitoring efficiency, optimizing resource allocation, and supporting sustainable agricultural practices.

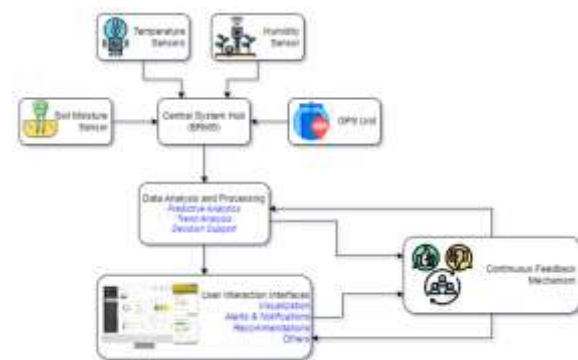
### SYSTEM DESIGN AND ARCHITECTURE

The results and the architecture design and design decisions for the IoT-Enabled Bamboo Resource Management System are presented in this article. The requirements-gathering cycle resulted in the identification and the development of specific system design goals, system architecture, and technical specifications (hardware and software), as well as the components of the data model. The next section delves into these elements, discussing their relevance and contribution towards the

establishment of a sustainable and effective bamboo resource management system.

### System design goals

Fig. 1. depicts the design objective and data communication of IoT-Enabled BRMS, with information on how the different components relate towards the efficient and sustainable bamboo resource management. The system hub as the hub which stores and works with the Central system. The hub is fed with real-time data by strategically located IoT Sensors like soil moisture, temperature, humidity sensors as well as GPS units placed into the bamboo fields. With these sensors, we can constantly observe the surroundings to present the important information flowing into the hub for the analysis.



**Fig. 1.** Conceptual design and data communication flow of the IoT-enabled Bamboo Resource Management System (BRMS)

The processing and analysis component features data analysis tools to perform predictive analytics, trend analysis, and decision support. It provides the basis for identifying trends that aid in predicting the invasion of pests in the field or water shortage. The refined data is then depicted as the UI, which is where the farmers and stakeholders directly interact (front-end interface). With this easy-to-understand dashboard, we should be able to deliver these useful insights, alerts, and recommendations that help with resource management and decision-making. This kind of feedback loop makes the system versatile to take user input to improve step-by-step and gradually. Thus, the diagram showcases how the BRMS modernizes agricultural techniques by employing innovative technology and data analytics

which facilitate bamboo cultivation in Northeastern Cagayan.

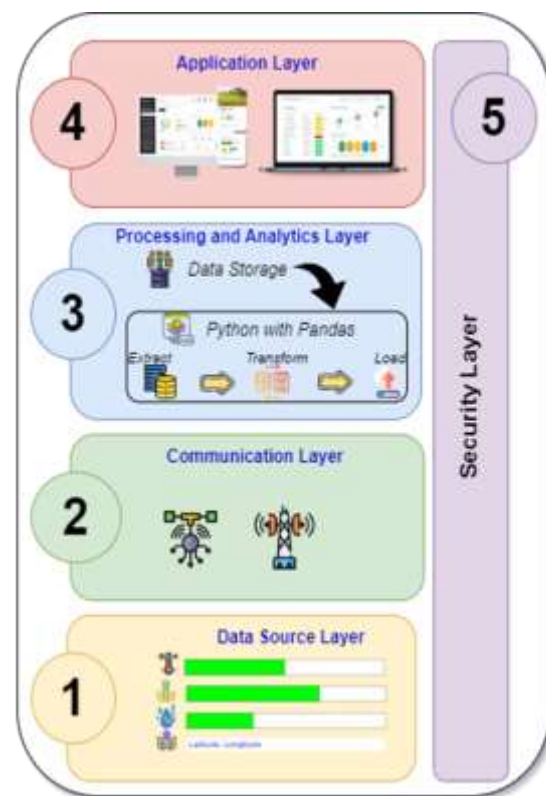
### System architecture

The system design, which incorporates various technologies and processes in the enhancement of bamboo cultivation and management, is illustrated in Fig. 2. The architecture consists of four hierarchical layers that form part of the system: Data Source, Communication, Processing and Analytics, and Application. These layers of the system work by the user to capture or extract the data that informs the actual user. In this model, the requirements of bamboo farming such as environmental monitoring, efficient resource allocation, and decision-making are satisfied. The Data Source Layer is the main component of the whole BRMS system. It comprises IoT sensors which are soil moisture sensors, temperature sensors, humidity sensors, GPS units, etc. So the sensors in the bamboo fields provide real-time data on the environment and the location of the bamboo resources. This data can be used to monitor the health and growth of bamboo, and to detect problems like poor irrigation, pests, or disease, and to take timely action. Moreover, the constant and precise data in this layer is pivotal for the subsequent processing and analysis of the data.

The Communication Layer links the devices on the field level with the system through Wi-Fi and cellular networks. This ensures that the data transfer is communicating timely, accurate and at security and low delays time less and low loss of packets. It prevents the quality of live monitoring from being devalued and that high volumes of data are processed at times when their processing is most beneficial.

The Processing and Analytics Layer, it's the analytic brain of your BRMS. It uses these data storage systems and truly advanced analytics (ML algorithms) integrated within the Processing and Analytics Layer which is the Analytical Center of BRMS. It is analyzed using sophisticated tools and techniques, utilizing such structures as (but not limited to) database storage, machine learning techniques and the like. This layer

recognizes patterns, forecasts trends, and bequeaths insights like weather prediction, early warnings of disease and timely harvests. It can help improve resource allocation, productivity development and sustainable bamboo management by making it more farmer and stakeholder led they will also be empowered to feedback in real time and raise an alert/decision support based on information from the field. It encourages user engagement and the adoption of smart agriculture practices.



**Fig. 2.** Layered system architecture of the IoT-enabled Bamboo Resource Management System (BRMS)

Data in the Security Layer is protected according to the encryption, authentication, and secure retention. Frequent updates and audits protect from cyber-attacks, cultivate user confidence, and guarantee the trustworthiness of data. The BRMS framework integrates IoT, communications, analytics, as well as UI into a single framework. Its multi-level design of data collection, transmission, analysis and consumer control helps to sustainably and data-driven bamboo management.

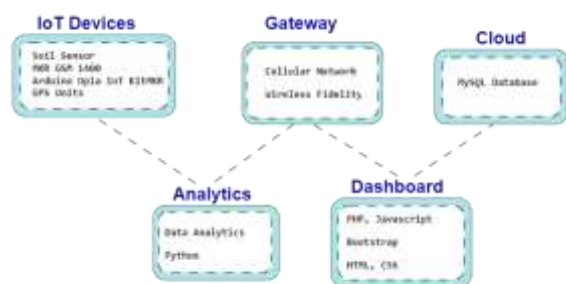
## Technical specifications

### Hardware and software components

The system integrates different sorts of hardware and software components (Fig. 3) to support effective data collection, processing, and visualisation.

### IoT devices

**Soil sensors:** IoT Devices Soil Sensors Soil sensors serve as an important sensor to monitor the environment including soil moisture, which are key factors in optimizing the water consumption and health of the bamboo. These sensors are equipped with real-time data, which assists to management of the irrigation system. As specified by Spandana and Pabboju (2023), sensors for soil moisture yield great advances in agricultural productivity, production cycle performance, and water saving.



**Fig. 3.** Hardware and software components of the proposed IoT-enabled Bamboo Resource Management System

**MKR GSM 1400:** The MKR GSM 1400 module provides wireless data transmission over a cellular network; it is suitable for countries where the internet access is only intermittent such as in those areas. It guarantees that IoT devices are talking to the central system with the same precision every 24 h. As noted by Chamara *et al.* (2023), GSM modules are vital for reliable communication in an IoT-based architecture.

**Arduino Opla IoT Kit MKR:** A versatile Arduino Opla IoT Kit MKR helps design, build and run IoT applications. It provides multiple sensors and connectivity capabilities to achieve data collection and system connectivity. As reported in the

documentation of Arduino and corroborated by Abbasi *et al.* (2022) the kit, facilitates development of IoT projects in an enhanced system.

**GPS Units:** GPS units are used to track the geography of bamboo resources, and provide accurate mapping and monitoring capabilities. This feature supports effective management of space distribution and resource allocation. Mohamed Ismail Ahmed (2021) highlights the importance of GPS technology in precision agriculture, stressing its effectiveness over human resources.

### Gateway

**Cellular network:** It is the cellular network gateway which allows sending data from IoT devices to the central system, especially in remote areas where Wi-Fi is absent. It provides constant connectivity in field sensors and maintains continuous data flow.

**Wireless fidelity (Wi-Fi):** Connecting IoT devices to the networking network with Wi-Fi gateways, local data flow is achieved via the gateways from your IoT devices, so you can reach a point in time that it doesn't suffer loss of control, as it does with the local data transmission, and enables direct interfacing between the sensor network and the central system. It facilitates effective and reliable data transfer in a small coverage area.

### Cloud

Cloud MySQL has now become one way to store all the IoT sensor and GPS unit data. The MySQL database provides a centralized database storing all data from IoT sensors and GPS units on the cloud. The database, with its organized and secured environment, also provides an efficient system for organizing and handling data well, in a ready-made way for efficient retrieval and analysis, it makes it easy to manage data as per need. MySQL's reliability and its ability to manage large datasets very well are known (Abbasi *et al.*, 2022).

### Analytics

**Data analytics:** It can work with data-based analysis like that developed in Python - It is crucial for

interpreting the huge data generated by the system. Python's libraries are Pandas, NumPy, scikit-learn which allow for advanced data analysis, trend detection, predictive modelling. Such tools allow the extraction of actionable insights useful for decision making for bamboo resource management decisions. The impact of data analytics and machine learning applications on Python data is highly documented (Nalini and Rama, 2022).

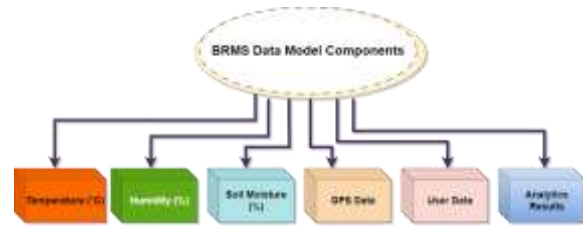
### Dashboard

PHP, JavaScript, and Bootstrap: Dashboard PHP, JavaScript, and Bootstrap: PHP is used for server-side scripting on the web-based dashboard with JavaScript used for interactivity and Bootstrap for responsive design. This unique combination has a dynamic and user-friendly interface that enables them to visualize data and interact in real-time. These technologies are also in conformance with best practices in the world of Web development (Spandana and Pabboju, 2023).

HTML and CSS: Dashboard interface is designed using HTML and CSS. With these technologies, the dashboard will be visually attractive and responsive as well as user-friendly with an easy navigation way for browsing and accessing information straight to the data. Their significance to web design is established in common design frameworks (Thilakarathne *et al.*, 2022).

### Data model components

Data Model Components IoT enabled bamboo resource system (BRMS) using a large database which is used to manage and analyze everything collected from sensors and inputs from users. The model facilitates sustainable biasing in agriculture sector to acquire usable recommendation for bamboo cultivation. A comprehensive set of key components (Fig. 4) which includes Temperature Data, Humidity Data, Soil moisture Data, GPS Data, User Data, and Analytics Results. They do so by allowing the overall functioning of the system, which enables accurate monitoring of various parameters, optimize resources and make data-based decisions.



**Fig. 4.** Data model structure of the IoT-enabled Bamboo Resource Management System (BRMS)

#### Temperature

Temperature data is vital to evaluate the environment in bamboo plantations. It helps measure temperature changes that impact growth and plant health. The best range of temperatures supports growth whilst extreme ranges cause stress, damage, and other side effects. Monitoring temperatures accurately is important to enhance agricultural management and improve crop yield (Binfield *et al.*, 2022).

#### Humidity

Humidity data is used as a complement to temperature monitoring, measuring the moisture content of the air. It provides information on the microclimate on the plantation, affecting plant transpiration and water need. Humidity data analysis helps farmers understand irrigation and disease prevention decisions (Mohamed Ismail Ahmed, 2021).

#### Soil moisture

Soil Moisture Data: Soil moisture data provides information about soil water content and is important in facilitating effective management of the irrigation. It is collected via sensors deployed in strategically located areas and measures bamboo to ensure sufficient plant exposure without over-irrigation. Adequate moisture in the soil can be expected to mitigate the drought stress and waterlogging due to insufficient usage of water and thus promote growth of a larger plant (Cesco *et al.*, 2023).

#### GPS

The GPS data can be used for accurate mapping and monitoring, the accurate geographic coordinates of bamboo resources are made available thanks to GPS data. Using GPS technology, precision agriculture may be enhanced. People can spot areas of use such as

irrigation and pest control that require specific attention. GPS application provides better spatial management and effective use of resources (Alam *et al.*, 2023).

#### User

User Data User data includes one's login credentials, titles and occupation data that are available to system users securely and individually. Managing user information helps the system to reach personalized insight in a data secure and transparent manner (Pathmudi *et al.*, 2023).

#### Analytics results

Analytics results are derived from processing the collected data using advanced algorithms and machine learning. These results reveal trends, predict, and give actionable instructions-for example predicting the impact of soil moisture or weather-to assist data-driven decision making (Kamilaris and Prenafeta-Boldú, 2018).

On the one hand, these elements together make up a complete data model that helps in the productive, effective, high efficient as well as sustainable management of bamboo by real-time monitoring and data analysis, informed decision making.

#### CONCLUSION

The IoT-enabled bamboo resource management system (BRMS) is one of the advanced farming technologies that significantly boost sustainable bamboo farming, especially in Northeastern Cagayan. This is achieved through the application of IoT technology to traditional farming which comes along with the IoT sensors, data analysis, and user-friendly tools for real-time monitoring and decision-making. The soil moisture, temperature, and humidity IoT sensors are integrated with GPS data and predictive analytics to provide the best input application of the needed resources while maintaining crop growth for efficiency and productivity. This also brings about smart farming which is developed through community empowerment by the increase in crop production and the decrease in resource wastage. The BRMS is effective in water management and chemical use. Its preventive measures may also aid in the reduction of climate change impacts, pest control, and

bamboo cultivation practices through the use of nature's predictability. The proposed method is applicable to other crop production under the shared concept of smart agriculture in the same area. The BRMS is not an ordinary or an issue of redundancy in another toolbox; it is transferring bamboo farming into a modern era or rather, changing the whole manufacturing process. It allows about instantaneous information, analytics, and easy use that together increase output; control the use of resources, and environmental sustainability. This is the reason why its instrumentality is recognized in the agricultural promotion of such regions as Northeastern Cagayan.

#### REFERENCES

- Abbasi R, Martinez P, Ahmad R.** 2022. The digitization of agricultural industry: A systematic literature review on agriculture 4.0. *Smart Agricultural Technology* **2**, 100042. <https://doi.org/10.1016/j.atech.2022.100042>
- Alam MFB, Tushar SR, Zaman SM, Gonzalez EDRS, Bari ABMM, Karmaker CL.** 2023. Analysis of the drivers of agriculture 4.0 implementation in emerging economies: Implications towards sustainability and food security. *Green Technologies and Sustainability* **1**(2), 100021. <https://doi.org/10.1016/j.grets.2023.100021>
- Binfield L, Britton TL, Dai C, Innes J.** 2022. Evidence on the social, economic, and environmental impact of interventions that facilitate bamboo industry development for sustainable livelihoods: A systematic map protocol. *Environmental Evidence* **11**(1), 1–12. <https://doi.org/10.1186/s13750-022-00286-8>
- Cesco S, Sambo P, Borin M, Basso B, Orzes G, Mazzetto F.** 2023. Smart agriculture and digital twins: applications and challenges in a vision of sustainability. *European Journal of Agronomy* **146**, 126809. <https://doi.org/10.1016/j.eja.2023.126809>
- Chamara N, Bai G, Ge Y.** 2023. AICropCAM: Deploying classification, segmentation, detection and counting deep-learning models for crop monitoring on the edge. *Computers and Electronics in Agriculture* **215**, 108420. <https://doi.org/10.1016/j.compag.2023.108420>

**Dhanaraju M, Chenniappan P, Ramalingam K, Pazhanivelan S, Kaliaperumal R.** 2022. Smart farming: Internet of Things (IoT)-based sustainable agriculture. *Agriculture* **12**(10), 1745.

<https://doi.org/10.3390/agriculture12101745>

**Gupta A, Kumar S, Singh P, Sharma V.** 2023. IoT-based smart agriculture monitoring system using machine learning and sensor networks. *Computers and Electronics in Agriculture* **206**, 107637.

**Kamilaris A, Prenafeta-Boldú FX.** 2018. Deep learning in agriculture: A survey. *Computers and Electronics in Agriculture* **147**, 70–90.

<https://doi.org/10.1016/j.compag.2018.02.016>

**Mohamed Ismail Ahmed DS.** 2021. The role of technology in small agricultural projects. *International Journal of Modern Agriculture and Environment* **1**(1), 1–21.

<https://doi.org/10.21608/ijmae.2023.215955.1015>

**Nalini T, Rama A.** 2022. Impact of temperature condition in crop disease analyzing using machine learning algorithm. *Measurement: Sensors* **24**, 100408.

<https://doi.org/10.1016/j.measen.2022.100408>

**Pathmudi VR, Khatri N, Kumar S, Abdul-Qawy ASH, Vyas AK.** 2023. A systematic review of IoT technologies and their constituents for smart and sustainable agriculture applications. *Scientific African* **19**, e01577. <https://doi.org/10.1016/j.sciaf.2023.e01577>

**Spandana K, Pabboju S.** 2023. IoT enabled smart agriculture using digital dashboard. *Indian Journal of Science and Technology* **16**(1), 1–11.

<https://doi.org/10.17485/ijst/v16i1.1680>

**Thilakarathne NN, Bakar MSA, Abas PE, Yassin H.** 2022. A cloud enabled crop recommendation platform for machine learning-driven precision farming. *Sensors* **22**(16), 6299.

<https://doi.org/10.3390/s22166299>