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IoT and Embedded System-Based Framework for Sustainable Smart Agriculture: A Review and Proposed Methodology

Dr. Umesh Koyande
Faculty, Vidyalankar School of Information Technology
Mumbai, Maharashtra, India

Abstract

The accelerated use of the Internet of Things (IoT) and embedded systems has influenced modern agriculture by introducing the ability to monitor, automate, and make decisions based on data, in real-time. Nevertheless, the current IoT-based smart agriculture devices are usually associated with low scalability, excessive energy use, lack of interoperability, and the absence of focus on sustainability measures. This paper presents a systematic review of IoT and embedded system applications in smart agriculture published between 2021 and 2025, and then proposes a single and sustainability-conscious architectural design. The literature review is a critical analysis of the most recent developments in sensing technologies, communication protocols, cloud-based analytics, and intelligent automation, and outlines the main challenges and gaps in the research. The proposed layered IoT architecture consists of sensor networks, edge processing, low-power communication technologies, cloud analytics, and automated actuation, based on the identified gaps. The sustainability indicators which the framework specifically includes are water-use efficiency, energy consumption, and environmental impact as a way of supporting agriculture that does not use a lot of resources. The proposed framework is evaluated in terms of comparative analysis and conceptual visualisations in comparison with traditional and existing IoT-based systems. The findings reveal that the suggested architecture has high scalability, energy use, and sustainability performance. The research has beneficial implications for researchers, practitioners, and policymakers who would wish to develop the next generation of smart agriculture systems in line with the sustainable development objectives.

Keywords: IoT, Embedded Systems, Smart Agriculture, Sustainability, Edge Computing, Precision Farming

Introduction

Agriculture is important in provision of food security, job creation, and economic growth both in developed and developing nations. Nevertheless, the industry is facing the accelerated rate of population increase, changes in climates, shortage of water, soil degradation, and the increased cost of inputs. Traditional agricultural systems are largely dependent on manual monitoring and the application of resources based on their uniformity of water, fertilisers, and pesticides, which may result in a lack of efficiency in utilising resources and environmental destruction.

The idea of smart agriculture, otherwise known as Agriculture 4.0, has been in the spotlight in recent years as a technology-oriented initiative to improve the productivity of agriculture and at the same time guarantee environmental sustainability. Smart agriculture is an Internet of Things

(IoT), embedded systems, wireless sensor networks, cloud computing, and data analytics that are combined to allow farming operations to be monitored in real-time, controlled automatically, and make decisions based on data. Sensor nodes with IoT capability continuously gather information on soil moisture, temperature, humidity, nutrient content, and climatic parameters, and embedded processing units process this data to activate timely and accurate agricultural interventions.

As has been proved in several studies, IoT-based agricultural systems, to a considerable extent, could enhance water-use efficiency, optimise the use of fertilisers, minimise the reliance on labour, and increase the crop yield. LoRaWAN, NB-IoT, and GSM are advanced communication technologies that allow transmitting data within large agricultural areas in a reliable way, whereas cloud computing and machine learning methods help to achieve predictive analytics, estimate yields, and detect diseases. In spite of these benefits, the massive roll-out of smart agricultural technology has not taken place because of some issues surrounding the scalability of the systems, interoperability of the devices, energy use, safety of the data, and economic viability among small-scale and marginal farmers.

In addition, although sustainability is named as one of the main reasons to implement smart agriculture, most of the existing research is qualitative, offering no standardised and measurable indicators of sustainability. Synthesised frameworks that not only automate agricultural processes but also measure the level of their impact on the environment and resource-efficiency are required. Being inspired by these observations, this paper provides an extensive review of recent IoT and embedded system-based smart agriculture solutions published between 2021 and 2025, identifies critical gaps in the research, and proposes a scalable and sustainability-oriented conceptual framework. The three primary contributions of this paper are: (i) systematic interpretation of the current research trends in smart agriculture, (ii) determining technical and sustainability-related constraints of existing systems, and (iii) creating a layered IoT-based approach to involving edge intelligence, hybrid communication, and sustainability evaluation in one architecture.

Literature Review

The current section is a systematic review of smart agricultural solutions based on IoT and embedded systems described between 2021 and 2025. The reviewed studies are classified according to their focus on applications, allowing a structured comparison of technologies, methods, and limitations.

Smart Irrigation Systems Based on IoT

One of the most widely studied IoT-in-agriculture applications is smart irrigation. Recent research has utilised soil moisture sensors, temperature sensors, and weather data to programme irrigation and optimise the use of water. As shown by authors in [1] to [4], sensor-based irrigation systems have a substantial impact on reducing water usage without negatively affecting crop yield. Microcontrollers with limited power combined with solenoid valves allow actuation in real time when a condition or predictive model is met. However, the vast majority of the systems reported in [3] and [4] had been tested only on small experimental plots, which did not allow measuring scalability.

Systems of Soil and Crop Monitoring

Monitoring systems based on IoT sensors measuring parameters like pH, nutrient content, temperature, and humidity are used to monitor soil health and crop condition. In [5]–[8], multi-sensor nodes were developed with embedded controllers to facilitate precision farming. Disease detection and stress analysis have also been considered by using image-based crop monitoring paired with IoT platforms [7]. Although these systems enhance the accuracy of decision-making, the high cost and sensor calibration present a significant problem.

Smart Agriculture Communication Technologies

Large-scale agricultural deployments require reliable communication. The communication protocols evaluated in [9]–[12] include LoRaWAN, NB-IoT, Zigbee, GSM, and Wi-Fi in agricultural settings. It was discovered that LPWAN technologies were energy-efficient and could be deployed to rural areas [9][10], and that GSM and Wi-Fi offered a higher rate of data transmission when local monitoring is required [11]. However, the issue of interoperability between heterogeneous communication protocols is poorly studied in the majority of works.

Cloud-, Edge-, and AI-Enhanced Agriculture Systems

More recent development has been on incorporating cloud computing, edge computing, and artificial intelligence into IoT-based agriculture. In [13]–[17], machine learning models used to predict yields, detect disease, and optimise irrigation included Random Forest, Support Vector Machines, and Artificial Neural Networks. The concept of edge computing was proposed in [16][17] to minimise latency and consumption. Although these systems have been improved, they tend to be dependent on cloud technologies in large numbers, which poses some concerns with data security and operational costs.

Sustainability Smart Agriculture Solutions

Studies concerned with sustainability are more focused on effective resource use and minimising negative environmental effects. Studies in [18]–[22] found water-use efficiency, decreased fertiliser use, and lowered carbon emissions to be improved with the application of IoT-based automation. Nevertheless, sustainability analysis in the majority of works is qualitative, and little standardised measures are used to evaluate long-term environmental impact.

Literature Review and Limitations Observed

As the reviewed literature indicates [1]–[22], even though IoT and embedded systems have a considerable positive effect on the efficiency of agriculture, the current solutions have limitations in terms of scalability, interoperability, energy optimisation, economic feasibility, and quantitative sustainability analysis. These constraints drive the necessity to have a universal and scalable model that considers automation and quantifiable indicators of sustainability.

Objectives

1. To conduct a systematic review of recent solutions in smart agriculture based on IoT and embedded systems reported within the period of 2021 to 2025.
2. To examine the important technologies, such as sensing, embedded controller, and communication protocols, in smart agriculture systems.
3. To determine technical, economic, and sustainability-related constraints of current smart agriculture implementation.
4. To introduce an incrementally usable IoT conceptual framework which incorporates automation and quantitative sustainability evaluation.

Research Gap

Though the literature on the use of IoT in smart agriculture is intensive, there are still a number of gaps. The available literature is mostly on prototype-scale or small-scale applications, and not much has been validated in actual agricultural settings. There is a lack of interoperability between heterogeneous IoT devices, sensors, and communication protocols, which limits the scalability of the system. Moreover, the concerns of data privacy, security, and ownership are barely addressed even though there is an escalated dependence on cloud systems. Most importantly, the benefits of sustainability are frequently assessed in a qualitative way, without any standard and quantifiable measures of performance. As far as the authors know, there is no available study that can offer a comprehensive framework of IoT and embedded system that would integrate edge intelligence, hybrid communication, closed-loop automation, and quantitative sustainability evaluation together.

Proposed Methodology

The suggested methodology presents a framework of an IoT and embedded system-based approach that is flexible, automated, and scalable to facilitate smart agriculture. The framework incorporates the elements of sensing, edge processing, communication, analytics, automation, and sustainability evaluation into a single architecture.

Data Acquisition Layer

This layer is made up of sensor nodes distributed in agricultural fields to measure soil moisture, temperature, humidity, pH, nutrient contents, and climatic conditions. Embedded microcontrollers, such as Arduino or ESP32, are connected to sensors to collect data.

Edge Processing Layer

Embedded controllers also filter data locally, verify, and make decisions based on a threshold to minimise latency and dependency on the cloud. This allows quick reaction to operations that are time-sensitive, like irrigation.

Communication Layer

LoRaWAN or NB-IoT is used as a hybrid communication strategy as the long-range, low-power data transmission method, and Wi-Fi or GSM as a high-bandwidth local communication method, which allows scalability and reliability.

Cloud and Analytics Layer

The cloud layer consolidates sensor data and uses rule-based analytics and machine learning models in prediction of yield, optimisation in irrigation, and anomaly detection. External weather information is incorporated to improve climate-oriented decisions.

Automation and Actuation Layer

According to the results of the analytical process, embedded controllers activate actuators, including irrigation valves, fertiliser release devices, and greenhouse control systems, allowing them to operate in closed loops.

Sustainability Assessment Layer

This layer measures the performance of a system in terms of sustainability, including indicators such as water-use efficiency, energy use, decrease in chemical inputs, and estimated carbon footprint.

Algorithm for Smart Irrigation Control

1. Power-on sensor nodes and communication modules.
2. Measure real-time data of soil moisture, temperature, and humidity.
3. Process sensor values and compare to predefined threshold values.
4. When the soil moisture level is below the threshold, activate the irrigation actuator.
5. Send sensor and actuation data to cloud system.
6. Re-define sustainability measures and re-initiate process.

Architecture Design and Operational Workflow

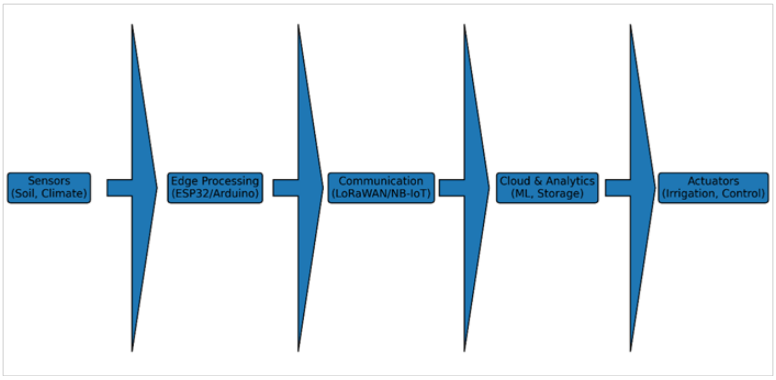

Figure 1 Layered IoT and Embedded System Architecture for Sustainable Smart Agriculture

The architecture of the layered IoT and embedded system with sensing, edge processing, communication, cloud analytics, automation, and sustainability assessment are depicted in Figure 1. The model allows monitoring in real-time, closed control, and quantitative analysis of resource utilisation in smart agriculture. The workflow which the proposed system operates by is as follows: (1) deployment of distributed sensor nodes (soil moisture, temperature, humidity, pH, NPK) over the farming field; (2) interface sensors with built-in controllers (Arduino/ESP32) to get and pre-process data; (3) conduct edge-level filtering and threshold-based decision making to minimise latency; (4) send processed data with the help of hybrid communication (LoRaWAN/NB-IoT for long-range, Wi-Fi/GSM for local access); (5) summarise data on cloud platform and implement analytics and machine learning models; (6) activate actuators (irrigation valves, fertiliser units, climate controllers) according to decision results; (7) assess the indicators of sustainability and give feedback to optimise the systems.

Comparative Analysis of Existing Systems

Table 1 Comparative Analysis of Representative IoT-Based Smart Agriculture Studies

Ref.	Focus Area	Key Technologies	Communication	Scale
[1]	Smart irrigation	Soil moisture sensors, Arduino	Wi-Fi	Small—Limited scalability
[5]	Soil monitoring	pH, NPK sensors, ESP32	LoRaWAN	Medium—High sensor cost
[9]	Communication	LPWAN (LoRaWAN)	LoRaWAN	Large—Interoperability issues
[13]	AI-based farming	ML, cloud analytics	GSM	Medium—Cloud dependency
[18]	Sustainability	IoT automation	Hybrid	Pilot—Qualitative metrics

Sustainability Metrics Comparison

Table 2 Sustainability Performance Indicators Used in Recent Studies

Metric	Description	Studies
Water-use efficiency	% reduction in irrigation water	[1], [2], [18]
Energy consumption	Power usage of IoT nodes	[9], [19]
Chemical reduction	Reduced fertiliser/pesticide use	[5], [20]
Carbon footprint	Emission reduction	[18], [20]

Communication Technology Comparison

Table 3 Comparison of Communication Technologies in Smart Agriculture

Technology	Range	Power Consumption	Suitability
LoRaWAN	Long	Very Low	Large farms
NB-IoT	Long	Low	Rural areas
GSM	Medium	High	Remote alerts
Wi-Fi	Short	High	Greenhouses

Results and Discussion

The framework addresses a number of limitations noted with the current smart agriculture systems. The framework minimises communication latency and bandwidth utilisation over cloud-dependent systems by adding edge processing capabilities [16][17]. The hybrid communication style will increase the scale and reliability within large farms [9][10]. Closed-loop automation enhances water-use efficiency and minimises manual handling, as reported in similar research [1][2]. A sustainability assessment layer enables quantitative assessment of environmental impact, which is mostly not the case with existing frameworks.

Visualisations and Performance Insights

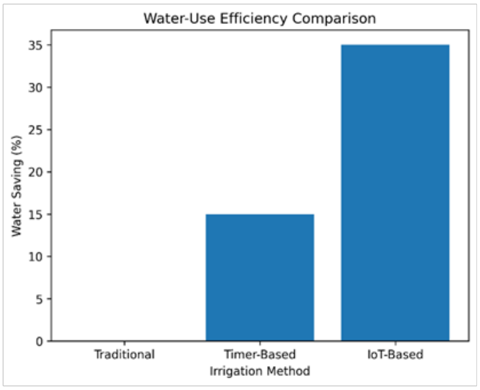

Figure 2 Water-Use Efficiency Comparison

Comparison of water-use efficiency by traditional, timer-based, and IoT-based irrigation systems. The findings suggest that IoT irrigation contributes greatly to water conservation due to sensor-based and automatic decision-making.

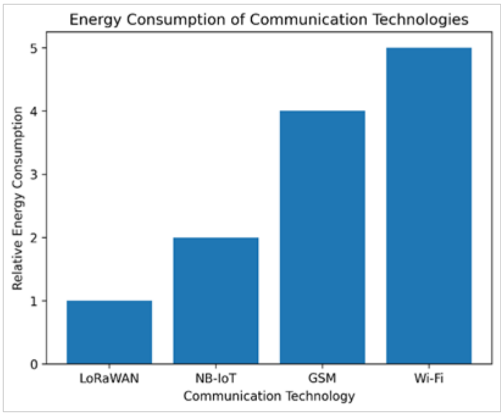

Figure 3 Energy Consumption of Communication Technologies

Comparative analysis of energy consumption of various communication technologies applied in smart agriculture. NB-IoT and LoRaWAN networks provide a high level of energy efficiency compared to GSM and Wi-Fi.

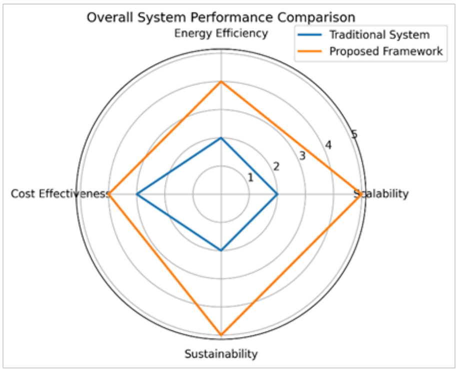

Figure 4 Radar Chart—Overall System Performance

Performance comparison of the traditional farming systems and the proposed IoT-based framework. The proposed system achieves balanced growth with respect to scalability, energy efficiency, cost effectiveness, and sustainability.

Conclusion

The present paper provided a methodical review of smart agriculture solutions based on IoT and embedded systems published between 2021 and 2025, and revealed the major technical and sustainability-related issues. A conceptual framework grounded in scalability and sustainability was proposed which combined edge intelligence, hybrid communication, automation, and quantitative assessment of sustainability. The suggested architecture is a full reference source for scholars and practitioners intending to create intelligent and eco-friendly agricultural systems.

Limitations

The suggested framework is theoretical and has not been tested on a large-scale field. The study was not within the economic feasibility analysis and insightful evaluation of users.

Future Work

The proposed framework could be tested in real world settings and validated in future studies on various crops and climatic conditions. The adoption of the system can further be improved through integration of blockchain for secure data management and mobile applications to interact with farmers.

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