

# IoT-Based Smart Agriculture: A Comparative Review of Sensors, Communication Technologies and Computing Architectures

Dr. Lakshminarayana K G<sup>1</sup>, Anagha K L<sup>2</sup>

<sup>1</sup>Associate Professor, Department of Electronics, Vijaya College Jayanagar, Bengaluru, India

<sup>2</sup>Student, Department of Computer Science and Engineering, BMS College of Engineering, Bengaluru, India

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**Abstract** - The Internet of Things (IoT) has become an important enabling technology for smart agriculture by connecting sensors, communication networks, computing platforms and agricultural equipment. These systems can provide continuous information about soil, crop and environmental conditions with support applications such as irrigation management, crop monitoring, greenhouse monitoring and resource optimisation. However, the suitability of an IoT technology depends on practical factors including communication range, energy consumption, network availability, processing requirements, deployment cost, interoperability and security. This paper presents a comparative review of major technological components used in IoT-based smart agriculture. Particular attention is given to agricultural sensors, wireless communication technologies, cloud, fog and edge computing with the integration of these components into field-level systems. Published studies are compared according to their sensing requirements, communication approach, processing architecture, application area and reported limitations. The comparison indicates that no single communication technology is appropriate for all agricultural environments. Long-range, low-power approaches are attractive for geographically distributed field sensing, while short-range and medium-range technologies remain useful for greenhouses and local sensor networks. Cloud computing provides extensive storage and processing, whereas edge and fog approaches can support lower-latency local processing and reduce unnecessary data transmission. The review also identifies continuing concerns related to energy, connectivity, cost, interoperability, sensor reliability and security. The paper concludes that practical smart agriculture requires technology selection based on application requirements rather than adoption of a single preferred platform.

**Key Words:** Internet of Things, Smart Agriculture, Sensors, LoRaWAN, NB-IoT, Edge Computing.

## 1. INTRODUCTION

Agriculture depends on timely decisions about water, soil condition, crop health, weather and the use of agricultural inputs. Conventional practices remain important, but they often depend on periodic observation and farmer experience. The increasing availability of low-cost sensors, embedded processors, wireless communication and internet services has created opportunities for continuous monitoring and data-assisted decision making.

IoT provides a framework in which physical devices can collect information, communicate with other devices or servers and support actions based on the collected data. The sensors used in agriculture measure soil moisture, temperature, humidity, electrical conductivity, pH and weather conditions, while actuators can operate pumps, valves, ventilation systems

and other equipment. Existing literature describes applications ranging from crop monitoring and disease prevention to irrigation control, soil management, greenhouse management and machinery control [1,2].

The agricultural environment differs from many conventional IoT deployments. Sensors may be distributed over large fields, access to mains electricity may be limited, wireless coverage may be inconsistent and devices may be exposed to moisture, dust, temperature variation and physical disturbance. Consequently, a technically suitable solution must consider the complete system rather than only the sensor or communication protocol.

The purpose of this paper is therefore to compare the main technological building blocks of agricultural IoT systems and to discuss their practical trade-offs. The paper is a comparative literature review rather than a report of a new experimental implementation.

## 1.1 Objectives

- ❖ To review the sensing technologies commonly used in IoT-based agriculture.
- ❖ To compare communication technologies used for agricultural sensor networks.
- ❖ To examine cloud, fog and edge computing approaches.
- ❖ To compare integrated systems reported in the literature.
- ❖ To identify practical challenges involving energy, connectivity, cost, security and interoperability.
- ❖ To identify areas where further research and field validation are needed.

## 2. REVIEW APPROACH

The literature reviewed in this manuscript was collected from publisher platforms and open-access sources available to the author, with emphasis on IEEE, Elsevier/ScienceDirect, Springer, MDPI, Frontiers and PLOS ONE publications. The collected material includes original research papers as well as review and survey papers. Review papers are used to establish background and identify important technology categories, while original studies are used for detailed comparisons of implementations and reported results.

The review was organized around four technological dimensions: sensing, communication, computing and application integration. For each relevant study, information of interest includes the sensing parameters, communication technology, computing location, application, reported performance or practical outcome and limitations. This approach is intended to avoid treating all IoT agricultural systems as equivalent.

## 2.1 Review Questions

- ❖ What types of sensors are most frequently used for agricultural IoT monitoring?
- ❖ How do communication technologies differ in range, energy use, data rate and infrastructure requirements?
- ❖ Where are cloud, fog and edge computing used in agricultural IoT systems?
- ❖ What combinations of technologies are used in practical systems?
- ❖ What limitations repeatedly appear across the literature?

## 3. IoT Architecture for Smart Agriculture

A typical agricultural IoT system can be viewed as a sequence of sensing, communication, processing and application functions. The boundaries between these layers vary among studies, but the functional arrangement is useful for comparison.

| Layer         | Main role                                                        | Typical components                                                               |
|---------------|------------------------------------------------------------------|----------------------------------------------------------------------------------|
| Sensing       | Collect physical and environmental information                   | Soil moisture, temperature, humidity, pH, EC, weather and imaging sensors        |
| Communication | Transfer measurements between field devices and gateways/servers | LoRaWAN, NB-IoT, ZigBee, Wi-Fi, BLE and cellular networks                        |
| Processing    | Store, aggregate, analyse and interpret data                     | Microcontrollers, gateways, cloud, fog and edge platforms                        |
| Application   | Present information or control agricultural operations           | Dashboards, mobile applications, irrigation control, alerts and decision support |

Table 1: IoT Architecture

The LoRaFarM implementation illustrates this layered approach in a practical farm setting. Its field modules contain sensors and actuators, a LoRaWAN gateway forwards data, middleware manages the information and higher-level modules provide farmer-oriented functions [3]. A related Cloud-Fog-Edge review also shows that agricultural systems increasingly combine computing paradigms according to application requirements [2].

## 4. Agricultural Sensing Technologies

Sensors form the primary information source for agricultural IoT systems. The usefulness of the complete system depends strongly on the quality, calibration, placement and durability of these sensors. Common parameters include soil moisture, soil temperature, air temperature, relative humidity, electrical conductivity, pH, rainfall, wind and solar radiation [5], [12], [13].

| Sensor / measurement            | Main use                                  | Advantages                                 | Important limitations                                       |
|---------------------------------|-------------------------------------------|--------------------------------------------|-------------------------------------------------------------|
| Soil moisture / water content   | Irrigation scheduling and soil monitoring | Directly related to water availability     | Placement, calibration and soil variability affect readings |
| Soil temperature                | Root-zone and soil-condition monitoring   | Simple and useful for environmental models | Local variation can be significant                          |
| Air temperature / humidity      | Microclimate and greenhouse monitoring    | Low-cost and widely available              | Requires suitable placement and protection                  |
| Electrical conductivity         | Soil and nutrient assessment              | Useful additional soil information         | Interpretation depends on soil conditions                   |
| pH                              | Soil condition assessment                 | Relevant to crop and nutrient management   | Calibration and maintenance are important                   |
| Weather sensors                 | Irrigation and environmental decisions    | Provides contextual information            | More sensors increase cost and maintenance                  |
| Imaging / multispectral sensing | Crop health and remote monitoring         | Large-area, non-contact observation        | Higher hardware, processing and data requirements           |

Table 2: Sensors Required

A 2025 NB-IoT soil monitoring study combines soil temperature, volumetric water content and electrical conductivity sensing with a weather station and GPS. The reported system also considers power management and long-distance communication, illustrating that sensor selection cannot be separated from network and deployment requirements [4].

Recent precision-agriculture literature also highlights sensor calibration, maintenance, durability, interoperability and data

accuracy as continuing challenges. Environmental factors such as soil composition and topography can influence sensor performance, while remote deployments may require sustainable power sources [5].

## 5. Wireless Communication Technologies

Communication is one of the most important design choices in agricultural IoT. Farms can contain devices spread across fields, greenhouses or livestock areas. The required range and data volume vary considerably between applications. A greenhouse monitoring system may operate with Wi-Fi or BLE, while an open field may require long-range low-power technology.

| Technology             | Typical strength                                        | Typical limitation                                | Potential agricultural use                              |
|------------------------|---------------------------------------------------------|---------------------------------------------------|---------------------------------------------------------|
| BLE                    | Low power and short-range connectivity                  | Limited range                                     | Local sensors and nearby devices                        |
| ZigBee / IEEE 802.15.4 | Low-power sensor networking                             | Requires suitable network topology/gateway        | Greenhouses and local WSNs                              |
| Wi-Fi                  | High data rate and common infrastructure                | Higher power and shorter practical field coverage | Greenhouses and local monitoring                        |
| LoRaWAN                | Long range and low-power field connectivity             | Low data rate and gateway/network planning        | Distributed field sensors                               |
| NB-IoT                 | Wide-area cellular connectivity and low-power operation | Depends on cellular/operator availability         | Remote soil and environmental monitoring                |
| 4G/5G cellular         | High data rate and wide-area access                     | Power and infrastructure requirements             | High-data applications, imaging and connected equipment |

Table 3: Communication Technologies

LoRa and LoRaWAN should also be distinguished. LoRa is a physical-layer modulation based on chirp spread spectrum, whereas LoRaWAN defines a network architecture and MAC layer around LoRa-based physical communication. The LoRaFarM study explains that increasing spreading factor improves sensitivity and range but reduces data rate and increases transmission duration and energy use [3].

The literature therefore does not support a universal statement that one protocol is best. Instead, communication should be selected according to field size, required data rate, latency, energy availability, network coverage and the availability of gateways or cellular infrastructure [3,6].

## 6. Cloud, Fog and Edge Computing

Agricultural IoT systems can generate continuous streams of sensor data. Cloud computing is useful for storage, long-term analysis and applications requiring substantial computational resources. However, sending every measurement to a remote cloud can increase communication load and latency. Fog and edge computing move some processing closer to the data source.

| Feature                | Cloud                             | Fog                                      | Edge                                             |
|------------------------|-----------------------------------|------------------------------------------|--------------------------------------------------|
| Processing location    | Remote data center                | Between field/edge and cloud             | At or very near devices/gateway                  |
| Computational capacity | High                              | Moderate                                 | Usually limited                                  |
| Latency                | Higher                            | Lower than cloud in suitable deployments | Very low for local operations                    |
| Internet dependence    | High                              | Moderate                                 | Can support local operation                      |
| Typical role           | Storage and large-scale analytics | Distributed processing and coordination  | Real-time filtering, control and local inference |

Table 4: Cloud-Fog-Edge Comparison

The Cloud-Fog-Edge literature notes that sending unnecessary data to the cloud can increase cost and processing requirements. Local processing can aggregate or filter information before transmission and can support real-time operation [2]. LoRaFarM also demonstrates the practical value of placing processing capability at a gateway so that some operations can continue during temporary internet loss [3].

## 7. Integrated Agricultural IoT Systems

The collected studies demonstrate that agricultural IoT systems are usually combinations of several technologies rather than single-technology solutions. The following examples illustrate the range of architectures found in the literature.

| Study / system                    | Sensing                                                 | Communication                        | Processing / platform                       | Application                                    |
|-----------------------------------|---------------------------------------------------------|--------------------------------------|---------------------------------------------|------------------------------------------------|
| LoRaFarM [3]                      | Soil moisture, soil temperature, greenhouse parameters  | LoRaWAN; local Wi-Fi inside a module | Gateway, middleware and database            | Farm and greenhouse monitoring/control         |
| PLOS ONE communication study [7]  | Humidity, temperature, water-level related measurements | IoT wireless communication           | Optimisation and deep learning              | Communication performance in smart agriculture |
| NB-IoT soil monitoring [4]        | Soil temperature, VWC, EC and weather                   | NB-IoT                               | IoT platform and ML-based prediction        | Farmland soil monitoring                       |
| NB-IoT irrigation system [8]      | Irrigation-related sensor measurements                  | NB-IoT                               | Three-layer system and application platform | Smart irrigation                               |
| Blynk/ThingSpeak irrigation [9]   | Soil moisture, temperature, humidity                    | Wi-Fi                                | ESP8266, Blynk and ThingSpeak               | Remote irrigation monitoring/control           |
| LoRa + edge irrigation study [10] | Soil moisture and meteorological sensors                | LoRa                                 | Edge gateway plus cloud/application         | Irrigation scheduling                          |

Table 5: IoT Systems

These examples show that the communication layer is strongly influenced by the physical environment. A Wi-Fi-based system can be practical where local infrastructure is available, while LoRaWAN or NB-IoT becomes more attractive when field devices are distributed over larger areas. The computing arrangement is similarly application-dependent.

The NB-IoT irrigation study reports a hardware cost of approximately US\$148.5–188 and a tested communication distance within 1600 m under its experimental conditions, while also identifying sensor reliability and power sustainability as limitations [8]. These values should be interpreted as results of that particular implementation and should not be generalised to all NB-IoT systems.

## 8. Comparative Discussion

The literature suggests four practical considerations should be examined together: sensing quality, connectivity, processing location and deployment constraints. Improving one component does not automatically improve the whole system. For example, a high-quality sensor is of limited practical value if its data cannot be transmitted reliably, while a strong communication link does not compensate for inaccurate sensor measurements.

| Design factor         | Questions for system selection             | Likely preferred approach (context dependent)                      |
|-----------------------|--------------------------------------------|--------------------------------------------------------------------|
| Field coverage        | How far apart are the devices?             | LoRaWAN or NB-IoT for wide-area deployments                        |
| Data volume           | Are measurements small or image-rich?      | LoRaWAN/NB-IoT for small telemetry; Wi-Fi/cellular for larger data |
| Latency               | Must decisions occur immediately?          | Edge/fog processing                                                |
| Internet availability | Can the field rely on continuous backhaul? | Local/edge operation where connectivity is unreliable              |

| Design factor | Questions for system selection                       | Likely preferred approach (context dependent)                           |
|---------------|------------------------------------------------------|-------------------------------------------------------------------------|
| Energy        | Are devices battery/solar powered?                   | Low-power sensing and LPWAN communication                               |
| Cost          | Can gateways and subscriptions be supported?         | Low-cost local/LPWAN designs, depending on site                         |
| Security      | What happens if devices or data are compromised?     | Device authentication, encryption, secure updates and controlled access |
| Scalability   | Will the farm add more devices or application areas? | Modular architectures and interoperable interfaces                      |

Table 6: Preferred systems for various design factors

## 9. Security, Energy and Deployment Challenges

Security is relevant at several layers of an agricultural IoT system. Sensor nodes, gateways, communication networks, cloud services and user applications may each present different attack surfaces. Previous literature categorizes agricultural IoT threats in terms of privacy, authentication, confidentiality, availability and integrity [2,11].

Energy is another persistent constraint. Sensor nodes may be installed in locations where battery replacement is inconvenient. Communication is often a major part of the energy budget, so duty cycling, local aggregation, low-power protocols and renewable energy harvesting can be useful. However, the actual benefit depends on the sensing frequency, radio configuration, weather and maintenance requirements. Deployment cost extends beyond the initial hardware price. Gateways, cellular subscriptions, cloud services, calibration, maintenance, replacement of damaged sensors and technical support should be considered when evaluating an agricultural IoT system. A low-cost prototype may therefore have a different total cost of ownership from a long-term farm deployment.

Interoperability is also important. A farm may contain devices from different manufacturers and may use more than one communication technology. The LoRaFarM architecture demonstrates one approach in which heterogeneous sub-networks can be integrated through a gateway, allowing different protocols and device capabilities to coexist [3].

## 10. Research Gaps

- ❖ Long-duration field validation under different soil, weather and crop conditions is still needed for many prototype systems.

- ❖ Sensor reliability, calibration and maintenance deserve greater attention alongside communication performance.
- ❖ Interoperability between heterogeneous sensors, gateways and software platforms remains a practical challenge.
- ❖ Edge computing and edge AI require further field-level evaluation, particularly under limited power and computing resources.
- ❖ Security mechanisms need to be evaluated in complete agricultural deployments rather than only at the algorithm level.
- ❖ Economic evaluation should include installation, maintenance, connectivity and replacement costs rather than only prototype hardware cost.
- ❖ Renewable-energy-assisted sensor deployments need validation across seasons and geographic conditions.

## 11. Future Directions

Future agricultural IoT systems are likely to become more modular, combining multiple communication technologies and computing locations. A field may use low-power sensors connected through LoRaWAN or NB-IoT while a local gateway performs filtering and control, with the cloud reserved for storage and long-term analytics. Such an arrangement can reduce unnecessary data transmission while retaining central visibility.

Edge AI is another promising direction. Rather than transferring all raw sensor or image data to a remote server, selected models can operate near the source. This may reduce latency and communication load, although model size, energy consumption and data quality must be considered.

Sustainable deployments will also require attention to power management, sensor durability, repairability and total cost of ownership. For small and medium farms, practical simplicity may be more important than the use of the newest technology.

## 12. CONCLUSIONS

This comparative review examined the major technological components of IoT-based smart agriculture, including sensing, communication and computing. The literature demonstrates that agricultural IoT is not a single technology but an integration of devices and services designed for particular field conditions. Soil and environmental sensors provide the basic information required for monitoring, while communication technologies determine how reliably and efficiently that information can be transferred. LoRaWAN and NB-IoT are useful options for many wide-area telemetry applications, whereas Wi-Fi, ZigBee and BLE remain relevant for local deployments. Cloud, fog and edge computing provide different trade-offs between computational capacity, latency, connectivity dependence and energy use.

The main conclusion is that technology selection should be application-driven. A successful agricultural IoT system must consider sensing accuracy, communication range, energy availability, processing requirements, security, cost and long-term maintenance together. Further field validation, interoperability, edge intelligence and sustainable power solutions are important areas for future work.

## ACKNOWLEDGEMENT

The authors acknowledge the support and encouragement received from their respective institutions during the preparation of this review article.

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