Sativa : Journal of Agricultural Sciences
E- ISSN : 3089-7807
Volume. 1 Issue 3 September 2025
Page No: 134-146

# Resilient IoT Architectures for Sustainable Agriculture: Analyzing Energy and Network Performance in Field Deployments

**Kamal**
**Universitas Muhammadiyah Sidenreng Rappang, Indonesia**
Correspondent: kamalpodding@gmail.com

Received : July 22, 2025
Accepted : September 11, 2025
Published : September 30, 2025

Citation: Kamal, (2025). Resilient IoT Architectures for Sustainable Agriculture: Analyzing Energy and Network Performance in Field Deployments. Sativa : Journal of Agricultural Sciences, 1(3), 134-146.

**ABSTRACT:** The integration of Internet of Things (IoT) technologies into agricultural systems has revolutionized precision farming, offering high-resolution environmental monitoring and real-time decision-making capabilities. This study evaluates the energy and network performance of IoT systems deployed in sub-hectare plots, focusing on the interplay between wireless transmission reliability, latency, packet loss, device uptime, and energy consumption. Utilizing a hybrid architecture combining edge computing and cloud-based data management, the system consisted of solar-powered sensor nodes transmitting soil and climate data at 5–60 minute intervals. Performance metrics were logged over a 90-day field trial. Results indicated an average transmission success rate exceeding 93% under optimal conditions, with latency ranging from 120 to 300 milliseconds. Packet loss increased during rainfall events, while energy consumption averaged 18 Wh/day per sensor. Adaptive duty-cycling and data buffering strategies proved effective in conserving energy and maintaining reliability. Environmental factors especially weather variability emerged as critical influences on both communication performance and power availability. The findings underscore the importance of integrated system design, including energy-harvesting strategies, low-power communication protocols, and resilient network architectures, for ensuring the viability of IoT systems in rural agriculture. This research contributes empirical benchmarks and design insights essential for developing robust, scalable IoT solutions tailored to smallholder farming contexts.

**Keywords:** IOT Agriculture, Energy Efficiency, Wireless Network Reliability, Smart Sensors, Latency, Packet Loss.



## INTRODUCTION

The increasing convergence of digital technologies with agricultural practices has ushered in a new era of smart farming, where the Internet of Things (IoT) plays a pivotal role in enhancing productivity and sustainability. The implementation of IoT in precision agriculture enables data-driven decision-making by integrating real-time information from environmental and soil sensors.

These technologies facilitate optimized resource allocation, thereby improving crop yields and reducing ecological impacts. In smallholder and sub-hectare farming contexts, IoT has become especially critical due to its potential to deliver high-resolution monitoring without requiring large-scale infrastructure. As farming practices adapt to meet global food demands and environmental constraints, the use of IoT represents a cornerstone of sustainable agricultural innovation.

A wide range of current IoT applications have demonstrated significant improvements in agricultural efficiency. Precision irrigation, for instance, leverages soil moisture sensors to tailor water usage to crop needs, reducing waste while enhancing plant health (Farooq et al., 2019; Navarro et al., 2020). Environmental sensors tracking temperature, humidity, and soil conditions support early disease detection and more effective pest control (Abunadi et al., 2022; Bayih et al., 2022). Beyond the field, IoT supports logistics optimization through GPS-enabled smart delivery systems and enhances livestock management via wearable health monitors (Joshi et al., 2024). Together, these tools represent a holistic, systems-based transformation in agronomic practices.

Despite these technological advances, the successful deployment of IoT in rural farming areas remains limited by environmental and infrastructural factors. Environmental variability including temperature fluctuations, precipitation, and humidity affects both sensor accuracy and network reliability (Khedkar et al., 2021). Rugged terrain and dispersed farm plots further challenge consistent connectivity, particularly in areas lacking robust telecommunications infrastructure (Ateya et al., 2023). These conditions can cause increased latency, packet loss, and degraded data fidelity, directly impacting the effectiveness of smart agricultural systems. In addition, IoT systems must dynamically adapt to shifting environmental conditions, placing a premium on intelligent data processing and adaptive network protocols (Bayih et al., 2022; Abunadi et al., 2022).

Network reliability is a central technical concern in field-deployed IoT systems. High device density can lead to network congestion and data bottlenecks, while physical obstructions from terrain or vegetation reduce signal strength and range (Ugwuanyi et al., 2021). These issues contribute to data packet loss, delayed transmission, and overall system instability (Sanjeevi et al., 2020). Maintaining network performance requires implementing redundancy mechanisms and robust communication protocols capable of self-regulation (Majumdar et al., 2023). Without such mechanisms, the potential benefits of IoT remain unrealized in many rural applications.

In response to these challenges, smallholder farms have adopted sensor-based monitoring to enhance sustainability and operational resilience. These systems allow farmers to monitor critical variables such as soil moisture, nutrient levels, and microclimate conditions using affordable sensors and mobile gateways (Jayaraman et al., 2016). The availability of high-resolution data supports precise application of inputs, reducing overuse of water and chemicals while maintaining yield quality (Joshi et al., 2024). Data aggregation and analytics also assist in yield prediction, field planning, and seasonal adaptation (Farooq et al., 2019). These capabilities are essential for aligning agricultural practice with the United Nations' Sustainable Development Goals, particularly those targeting food security and responsible resource use (Khedkar et al., 2021).

Nevertheless, the trade-off between data resolution and energy efficiency remains a persistent issue. High-frequency data sampling increases insight accuracy but also places significant demands on power resources, especially for off-grid, battery-powered IoT devices (Wong & Wan, 2019).

Energy constraints limit system uptime and reliability, particularly in regions with inconsistent solar exposure or limited battery infrastructure. Determining the optimal sampling frequency one that balances the need for granular data with power conservation is a complex but critical task (Jayaraman et al., 2016). Technologies such as low-power wide-area networks (LPWAN) and intelligent scheduling algorithms offer partial solutions, but further innovation is needed to sustain long-term deployments in diverse field conditions (Amiri-Zarandi et al., 2022).

A focused body of research has begun to address the specific performance benchmarks required for IoT systems deployed in sub-hectare agricultural plots. These benchmarks include latency thresholds, acceptable packet loss percentages, transmission success rates, and energy usage metrics (Yadav et al., 2024). Systematic studies in real-world field environments help to contextualize these metrics, offering guidance on practical expectations for system reliability (Lorenzo et al., 2018). This is particularly important for smallholder operations, where cost-efficiency and ease of use must be prioritized. Tailoring IoT architectures to fit the unique constraints and opportunities of small-scale farming remains an ongoing area of innovation (Dogani et al., 2021).

The present study builds upon this body of knowledge by analyzing the real-world performance of IoT systems operating under rural field conditions. It aims to quantify the relationship between network metrics such as latency, packet loss, and transmission success and the energy requirements of solar-powered smart sensors. By doing so, it contributes empirical evidence necessary to refine deployment strategies for resilient and efficient IoT agriculture. The novelty of the study lies in its sub-hectare focus, real-time network assessment, and integration of power metrics under variable environmental conditions. Ultimately, this research seeks to inform the development of adaptable IoT frameworks that can support precision agriculture in underserved and remote regions where technology adoption is both vital and challenging.

## METHOD

This study was designed to evaluate the energy and network performance of IoT systems deployed in sub-hectare agricultural settings. The methodology encompasses system architecture, power configuration, and performance metric evaluation. This section outlines the physical and digital setup of the monitoring systems, data collection procedures, and criteria for performance analysis.

### System Architecture and Deployment

The IoT architecture used in this study integrated both cloud and edge-computing models to accommodate the challenges of field-based monitoring. Sensor nodes equipped with soil and microclimate sensing capabilities were deployed across smallholder plots, each ranging from 0.25 to 1 hectare. These sensors collected data on soil moisture, temperature, electrical conductivity, pH, NPK levels, air humidity, solar radiation, rainfall, and wind speed.

Each sensor node communicated wirelessly with a local IoT gateway. The gateway handled preliminary data processing using an edge-computing paradigm, which reduced the latency associated with cloud transmission. Processed and buffered data were then sent to a cloud server for long-term storage and advanced analytics. This hybrid architecture leveraged the benefits of both centralized (cloud) and decentralized (edge) models, ensuring flexibility and reducing bandwidth dependency (Aravind & Maddikunta, 2024; Effah et al., 2023).

Data visualization and user control interfaces were accessible via mobile and web dashboards, enabling farmers and researchers to interact with the system in real time. An MQTT protocol governed the communication between nodes and the cloud, ensuring lightweight data transfer and minimal overhead.

### Power Configuration of IoT Nodes

All IoT nodes were powered using solar photovoltaic panels paired with lithium-ion deep-cycle batteries. The photovoltaic panels harvested solar energy during the day, which was regulated and stored via an energy management system (EMS). The EMS was responsible for balancing power input and consumption, and for enforcing power-saving modes when necessary (Saraereh et al., 2020).

Devices operated under duty-cycling mechanisms, switching between active and sleep modes to conserve energy. During low-light or cloudy conditions, the battery packs ensured continued operation, albeit sometimes at reduced sampling frequency. This configuration provided the system with robust energy autonomy, particularly important in off-grid rural contexts.

To mitigate risks of solar-only dependency, the system was also designed to allow integration of secondary energy sources, such as wind or thermal generators. While not implemented in the current study, this hybrid-ready architecture ensured future scalability and resilience (Gong et al., 2024).

### Data Acquisition and Logging Frequency

Sensor readings were collected at intervals ranging from 5 to 60 minutes, depending on the variable. Soil moisture, air temperature, and humidity were logged every 5 minutes; pH and EC every 30–60 minutes. Rainfall data were event-based. Sensor data were timestamped and stored locally before synchronization with the gateway.

IoT network metrics were collected on an hourly basis and aggregated daily. These metrics included transmission success rate (%), latency (ms), packet loss (%), device uptime (%), and energy consumption (Wh/day).

### Performance Evaluation Metrics

Several standard performance metrics were used to assess the effectiveness of the deployed system. These include:

- Packet Delivery Ratio (PDR): The ratio of successfully delivered packets to the total number sent, reflecting system reliability (Jothikumar et al., 2021).
- End-to-End Delay: The time taken for a data packet to traverse from the sensor node to the cloud server. High delay indicates congestion or inefficiency in routing.
- Energy Consumption: Measured in watt-hours per day (Wh/day), this metric captures the average daily energy usage of each IoT node. It reflects the power efficiency and operational sustainability of the system.
- Network Lifetime: Indicates how long the network remains operational before critical nodes fail due to energy depletion. This is crucial for evaluating the system's longevity in field applications.
- Latency: Defined as the average time taken for sensor data to be accessible on the user interface, latency is critical for real-time applications like irrigation or disease response.
- Throughput: Measures the volume of data successfully transmitted over time. It is essential for understanding the system's effective bandwidth and data capacity.

These metrics were analyzed over a 90-day monitoring period to capture variations due to environmental changes, sensor load, and network conditions. Evaluating this performance spectrum allowed for comprehensive insights into the strengths and weaknesses of the current IoT implementation in rural precision agriculture.

By employing a hybrid architectural model, solar-powered energy management strategies, and standardized performance metrics, this study aims to provide a replicable framework for smallholder-friendly IoT deployments. These methodological considerations reflect the real-world constraints and needs of smart agriculture systems, offering a practical foundation for scalable and sustainable field applications.

## RESULT AND DISCUSSION

This section presents the core findings of the study, categorized under three primary aspects: IoT network reliability, power consumption trends, and the interaction between latency and data fidelity. The results are contextualized using empirical data and relevant literature benchmarks.

### IoT Network Reliability

The performance evaluation revealed that under clear weather and optimal deployment conditions, the wireless transmission success rate across IoT nodes exceeded 93%, aligning with the general benchmark range of 95% to 99% found in the literature (Raza et al., 2017). However, during adverse conditions such as rain and high humidity, the success rate dropped to approximately 90%, highlighting the sensitivity of wireless signals to environmental interference.

Latency, defined as the time delay between sensor data generation and its appearance on the user interface, fluctuated between 120 and 300 milliseconds. While values below 200 ms were considered acceptable for real-time agricultural decision-making, higher latency intervals compromised the timeliness of actions such as automated irrigation or pest treatment. These findings are consistent with studies emphasizing the need for low latency to preserve data usability in time-sensitive scenarios (Shan et al., 2022).

Packet loss increased notably during rainfall and dense cloud cover, with rates peaking at 7%. Environmental factors like physical obstructions (trees, crops, uneven terrain) and radio interference significantly contributed to this degradation. These results echo previous observations where network congestion and signal attenuation led to compromised data reliability (Ameloot et al., 2021).

Device uptime, a critical metric for system continuity, remained above 95% during the study period. Monitoring software recorded system logs to identify and analyze instances of downtime. Optimization strategies such as low-power transmission modes and predictive maintenance algorithms contributed to sustaining high uptime rates (Outferdine et al., 2024).

### Power Consumption Trends

The average daily energy consumption of each sensor node was approximately 18 Wh/day. These values align with established power consumption levels of LPWAN devices like LoRa, which typically range from 10 to 50 milliwatts during active states and far lower during sleep cycles (Diviacco et al., 2022).

Solar-powered sensors exhibited high reliability under clear skies, but their performance dropped under prolonged cloudy conditions. Energy deficits during overcast periods resulted in reduced sampling frequencies or temporary node inactivity. These findings support earlier studies emphasizing the impact of weather on energy harvesting in agricultural contexts (Vijayan et al., 2023).

To counter these limitations, several energy optimization strategies were implemented:

- Duty Cycling: Enabled nodes to remain in sleep mode between transmissions, reducing energy draw.
- Data Aggregation: Minimized transmission load by pre-processing data at the node level.
- Adaptive Protocols: Adjusted transmission frequency based on network conditions.
- Low-Power Technologies: Integrated energy-efficient communication standards like LoRa and Zigbee.

Power usage data were validated using dedicated monitoring equipment that recorded voltage, current, and internal temperature. These values were compared against baseline measurements obtained under controlled laboratory conditions to ensure accuracy and consistency. Data smoothing algorithms further enhanced the reliability of energy consumption trends (Fhaizal et al., 2021).

## Latency vs. Data Fidelity

Sensor sampling frequency was found to have a direct impact on network traffic and latency. Nodes configured to sample soil and atmospheric variables every 5 minutes generated substantially higher traffic, which, under certain bandwidth conditions, resulted in packet congestion and delivery delays. This aligns with findings from Fhaizal et al. (2021), who highlight the need to balance data frequency and network load.

High latency was shown to degrade data quality by reducing its temporal relevance. In applications requiring immediate intervention such as irrigation, nutrient delivery, or disease suppression delayed data reporting undermined decision accuracy. Several studies have underscored this point, warning against latency-induced inefficiencies in smart farming (Shan et al., 2022).

Weather disruptions had measurable effects on communication reliability. Heavy rainfall and high wind episodes led to packet losses and occasional node disconnects. These events underscored the importance of system resilience and redundancy in sensor networks, confirming observations by Ameloot et al. (2021).

To balance energy efficiency with latency requirements, the system employed adaptive sampling intervals. During periods of low variability or at night, sensors operated at reduced frequencies. Under dynamic conditions, such as temperature shifts or impending storms, sampling rates increased. This dynamic scheduling allowed the system to conserve energy while maintaining acceptable latency levels (Valente et al., 2020). Additionally, the adoption of ultra-narrowband protocols further optimized performance during high-latency scenarios, ensuring data delivery with minimal energy expenditure.

Collectively, the results demonstrate that IoT systems in smallholder agricultural settings can achieve high performance when designed with environmental adaptability and energy sensitivity. These outcomes contribute to a growing body of research focused on developing robust, sustainable, and field-ready IoT infrastructure for precision agriculture.

The findings of this study confirm the feasibility and challenges of deploying IoT systems in rural agricultural contexts, particularly within sub-hectare plots where infrastructural constraints and environmental variability significantly influence performance. Several design considerations emerge as critical to optimizing both energy efficiency and data reliability.

In terms of system design, an integrated approach is essential for managing the dual imperatives of energy conservation and data flow efficiency. Utilizing renewable energy sources particularly solar is foundational for sustaining operations in off-grid locations. Moreover, incorporating energy harvesting technologies such as piezoelectric systems or wind turbines could further enhance energy autonomy (Avallone et al., 2024). Optimizing data flow through compression algorithms reduces transmission volume and bandwidth consumption, enabling faster and more efficient communication (Callebaut et al., 2021).

Adaptive duty-cycling plays a vital role in extending battery life. Devices that dynamically adjust their activity cycles based on environmental inputs and energy availability can maintain longer operational periods while minimizing unnecessary power use (Balsamo et al., 2016). Similarly, network topology optimization, such as reducing the number of transmission hops, can significantly reduce both energy consumption and transmission delays (Codeluppi et al., 2020). The choice of communication protocol is equally important. Low-power options like LoRaWAN and NB-IoT enable extended transmission ranges with minimal energy draw, which is ideal for large or sparsely connected agricultural zones (Centenaro et al., 2016).

Beyond design, resilience strategies such as buffering and duty-cycling are essential for maintaining data integrity and system reliability in the face of network instability. Data buffering provides temporary storage for sensor readings during transmission downtimes, ensuring that no critical information is lost during brief outages (Zhang et al., 2019). Duty-cycling, especially when paired with wake-up radio mechanisms, allows devices to remain inactive while still responsive to essential signals preserving battery life without sacrificing performance (Aoudia et al., 2016). When properly implemented, these strategies significantly reduce latency and increase overall reliability, especially in regions affected by unpredictable weather patterns (Sultania et al., 2020).

Despite these advances, current agricultural IoT frameworks still face several limitations. Integration challenges persist, particularly due to the lack of standardized communication protocols. This hinders interoperability among devices from different manufacturers, increasing system complexity and cost (Jawad et al., 2017). Scalability also remains an issue, with many solutions tailored for small pilot programs rather than larger, more complex farm operations. Scaling often requires significant additional investment in infrastructure and coordination (Jawad et al., 2017).

Another critical concern is the dependence on power supplies. Even with energy-efficient designs, reliance on battery storage can lead to system failure if recharging conditions are not met. In remote locations, poor solar availability or battery degradation can interrupt services, highlighting the need for hybrid energy systems and predictive energy management (Miro-Panades et al., 2023). Moreover, environmental exposure continues to be a weak point. Many devices are not adequately weatherproofed, making them vulnerable to damage and data inconsistency during storms, heavy rainfall, or temperature extremes (Ameloot et al., 2021).

Designing for weather resilience is thus paramount for ensuring long-term performance. Devices that are physically robust and weather-sealed experience fewer failures, longer lifespans, and more reliable data collection over time (Kombo et al., 2021). Consistent data quality depends heavily on the ability of systems to maintain functionality during environmental stressors. Incorporating redundant communication paths and using robust antenna designs can help mitigate some of these disruptions (Vijayan et al., 2023).

Beyond technical reliability, weather-resilient IoT systems contribute to cost reductions by minimizing repair needs and system downtime. These reductions in operational interruptions translate into improved farming decisions, optimized irrigation schedules, and efficient fertilizer applications all of which contribute to more sustainable resource use (Chand et al., 2021). By supporting responsive and context-aware agricultural practices, weather-resilient systems ultimately foster improved productivity and environmental stewardship.

In summary, the study confirms that IoT systems can achieve high operational performance and energy efficiency when deployed with consideration for environmental factors and system-level constraints. Optimization strategies ranging from architecture selection and energy harvesting to buffering and protocol selection collectively shape the resilience and scalability of smart agriculture solutions. Future research should continue addressing the standardization, scalability, and environmental robustness of IoT systems to enhance their role in achieving sustainable agricultural development, especially for smallholder farms.

## CONCLUSION

This study has investigated the energy and network performance dynamics of IoT systems deployed in sub-hectare agricultural settings, focusing on the real-world operational behavior of smart sensors and communication infrastructure. The results confirm that under favorable environmental conditions, such systems can deliver high transmission success rates, minimal latency, and consistent energy usage all essential for reliable agricultural monitoring and decision-making.

Key findings include the observation that wireless transmission success rates exceeded 93% in clear weather, with latency generally remaining below 200 milliseconds sufficient for most real-time applications such as irrigation scheduling. Packet loss was notably higher during adverse weather, peaking at 7% during rain events, highlighting the vulnerability of wireless communication in dynamic field environments. Energy consumption was also found to be consistent, averaging 18 Wh/day per sensor node, although reliability declined during extended periods of low solar irradiance.

The study also demonstrated the effectiveness of various system design strategies such as adaptive duty-cycling, data buffering, low-power communication protocols, and edge-computing architectures in enhancing both energy efficiency and data reliability. Furthermore, the integration of solar power with battery storage provided the necessary energy autonomy for off-grid deployments, while highlighting the importance of weather-resilient system configurations.

This research contributes to the growing body of knowledge on precision agriculture by offering empirical benchmarks for IoT system deployment in smallholder farms. It provides actionable insights into the interplay between environmental variables, network metrics, and power consumption key elements in developing robust and scalable smart farming technologies. The findings underscore the necessity for holistic system design that accounts for environmental unpredictability, energy limitations, and the need for reliable, real-time data to support decision-making.

Future work should focus on refining multi-source energy integration, enhancing communication robustness through protocol innovation, and promoting interoperability across sensor platforms.

As IoT adoption expands, addressing these challenges will be crucial for the long-term viability and scalability of smart agriculture in resource-constrained environments.

## REFERENCE

Abunadi, I., Rehman, A., Haseeb, K., Parra, L., & Lloret, J. (2022). Traffic-Aware Secured Cooperative Framework for IoT-Based Smart Monitoring in Precision Agriculture. *Sensors*, *22*(17), 6676. https://doi.org/10.3390/s22176676

Ameloot, T., Torre, P. V., & Rogier, H. (2021). Variable Link Performance Due to Weather Effects in a Long-Range, Low-Power LoRa Sensor Network. *Sensors*, *21*(9), 3128. https://doi.org/10.3390/s21093128

Amiri-Zarandi, M., Fard, M. H., Yousefinaghani, S., Kaviani, M., & Dara, R. (2022). A Platform Approach to Smart Farm Information Processing. *Agriculture*, *12*(6), 838. https://doi.org/10.3390/agriculture12060838

Aoudia, F. A., Gautier, M., & Berder, O. (2016). OPWUM: Opportunistic MAC Protocol Leveraging Wake-Up Receivers in WSNs. *Journal of Sensors*, *2016*, 1–9. https://doi.org/10.1155/2016/6263719

Aravind, K., & Maddikunta, P. K. R. (2024). Optimized Fuzzy Logic Based Energy-Efficient Geographical Data Routing in Internet of Things. *Ieee Access*, *12*, 18913–18930. https://doi.org/10.1109/access.2024.3354174

Ateya, A. A., Bushelenkov, S., Muthanna, A., Paramonov, A., Koucheryavy, A., Chelloug, S. A., & El-Latif, A. A. A. (2023). Multipath Routing Scheme for Optimum Data Transmission in Dense Internet of Things. *Mathematics*, *11*(19), 4168. https://doi.org/10.3390/math11194168

Avallone, G., Landi, G., Granata, V., Notte, L. L., Palma, A. L., Sdringola, P., Puglisi, G., Pagano, S., & Barone, C. (2024). A Comparative Evaluation of IoT Electronic Solutions for Energy Harvesting. *Nano Express*, *5*(3), 032001. https://doi.org/10.1088/2632-959x/ad7a90

Balsamo, D., Weddell, A. S., Das, A., Arreola, A. R., Brunelli, D., Al-Hashimi, B. M., Merrett, G. V., & Benini, L. (2016). Hibernus++: A Self-Calibrating and Adaptive System for Transiently-Powered Embedded Devices. *Ieee Transactions on Computer-Aided Design of Integrated Circuits and Systems*, *35*(12), 1968–1980. https://doi.org/10.1109/tcad.2016.2547919

Bayih, A. Z., Morales, J., Assabie, Y., & By, R. A. d. (2022). Utilization of Internet of Things and Wireless Sensor Networks for Sustainable Smallholder Agriculture. *Sensors*, *22*(9), 3273. https://doi.org/10.3390/s22093273

Callebaut, G., Leenders, G., Mulders, J. V., Ottoy, G., Strycker, L. D., & Perre, L. V. d. (2021). The Art of Designing Remote IoT Devices—Technologies and Strategies for a Long Battery Life. *Sensors*, *21*(3), 913. https://doi.org/10.3390/s21030913

Centenaro, M., Vangelista, L., Zanella, A., & Zorzi, M. (2016). Long-Range Communications in Unlicensed Bands: The Rising Stars in the IoT and Smart City Scenarios. *Ieee Wireless Communications*, *23*(5), 60–67. https://doi.org/10.1109/mwc.2016.7721743

Chand, A. A., Prasad, K. A., Mar, E., Dakai, S., Mamun, K. A., Islam, F. R., Mehta, U., & Kumar, N. M. (2021). Design and Analysis of Photovoltaic Powered Battery-Operated Computer Vision-Based Multi-Purpose Smart Farming Robot. *Agronomy*, *11*(3), 530. https://doi.org/10.3390/agronomy11030530

Codeluppi, G., Cilfone, A., Davoli, L., & Ferrari, G. (2020). LoRaFarM: A LoRaWAN-Based Smart Farming Modular IoT Architecture. *Sensors*, *20*(7), 2028. https://doi.org/10.3390/s20072028

Diviacco, P., Iurcev, M., Carbajales, R., Potleca, N., Viola, A., Burcă, M., & Busato, A. (2022). Monitoring Air Quality in Urban Areas Using a Vehicle Sensor Network (VSN) Crowdsensing Paradigm. *Remote Sensing*, *14*(21), 5576. https://doi.org/10.3390/rs14215576

Dogani, J., Farahmand, M., & Daryanavard, H. (2021). A New Method to Detect Attacks on the Internet of Things (IoT) Using Adaptive Learning Based on Cellular Learning Automata. *Etri Journal*, *44*(1), 155–167. https://doi.org/10.4218/etrij.2021-0044

Effah, E., Thiaré, O., & Wyglinski, A. M. (2023). A Tutorial on Agricultural IoT: Fundamental Concepts, Architectures, Routing, and Optimization. *Iot*, *4*(3), 265–318. https://doi.org/10.3390/iot4030014

Farooq, M. S., Riaz, S., Abid, A., Abid, K., & Naeem, M. A. (2019). A Survey on the Role of IoT in Agriculture for the Implementation of Smart Farming. *Ieee Access*, *7*, 156237–156271. https://doi.org/10.1109/access.2019.2949703

Fhaizal, F. F., Suboh, S. M., & Ali, R. (2021). Development of Solar-Powered Crop Soil Conditions Monitoring System Using Internet of Things (IoT). *Journal of Physics Conference Series*, *2107*(1), 012034. https://doi.org/10.1088/1742-6596/2107/1/012034

Gong, Y., Yoon, I., & Noh, D. K. (2024). Optimizing the Charging Mobility of WPT-Enabled UAV to Enhance the Stability of Solar-Powered LoRaWAN IoT. *Energies*, *17*(7), 1617. https://doi.org/10.3390/en17071617

Jawad, H. M., Nordin, R., Gharghan, S. K., Jawad, A. M., & Ismail, M. (2017). Energy-Efficient Wireless Sensor Networks for Precision Agriculture: A Review. *Sensors*, *17*(8), 1781. https://doi.org/10.3390/s17081781

Jayaraman, P. P., Yavari, A., Georgakopoulos, D., Morshed, A., & Zaslavsky, A. (2016). Internet of Things Platform for Smart Farming: Experiences and Lessons Learnt. *Sensors*, *16*(11), 1884. https://doi.org/10.3390/s16111884

Joshi, D., Gupta, S., Vishwakarma, A., & Jagtap, S. (2024). Why IoT Enablement of Agrifood Transportation Disappoints Its Stakeholders: Unravelling Barriers for Enhanced Logistics. *Journal of Food Quality*, *2024*(1). https://doi.org/10.1155/2024/9289098

Jothikumar, C., Ramana, K., Chakravarthy, V., Singh, S., & Ra, I.-H. (2021). An Efficient Routing Approach to Maximize the Lifetime of IoT-Based Wireless Sensor Networks in 5G and Beyond. *Mobile Information Systems*, *2021*, 1–11. https://doi.org/10.1155/2021/9160516

Khedkar, S. P., Canessane, R. A., & Najafi, M. L. (2021). Prediction of Traffic Generated by IoT Devices Using Statistical Learning Time Series Algorithms. *Wireless Communications and Mobile Computing*, *2021*(1). https://doi.org/10.1155/2021/5366222

Kombo, O. H., Kumaran, S., & Bovim, A. (2021). Design and Application of a Low-Cost, Low-Power, LoRa-GSM, IoT Enabled System for Monitoring of Groundwater Resources With Energy Harvesting Integration. *Ieee Access*, *9*, 128417–128433. https://doi.org/10.1109/access.2021.3112519

Lorenzo, B., García-Rois, J., Li, X., González-Castaño, F. J., & Fang, Y. (2018). A Robust Dynamic Edge Network Architecture for the Internet of Things. *Ieee Network*, *32*(1), 8–15. https://doi.org/10.1109/mnet.2018.1700263

Majumdar, P., Bhattacharya, D., & Mitra, S. (2023). *Utilities of 5G Communication Technologies for Promoting Advancement in Agriculture 4.0: Recent Trends, Research Issues and Review of Literature*. 111–125. https://doi.org/10.1007/978-981-99-3668-7_6

Miro-Panades, I., Tain, B., Christmann, J., Coriat, D., Lemaire, R., Jany, C., Martineau, B., Chaix, F., Waltener, G., Pluchart, E., Noël, J.-P., Makosiej, A., Montoya, M., Bacles-Min, S., Briand, D., Philippe, J.-M., Thonnart, Y., Valentian, A., Heitzmann, F., & Clermidy, F. (2023). SamurAI: A Versatile IoT Node With Event-Driven Wake-Up and Embedded ML Acceleration. *Ieee Journal of Solid-State Circuits*, *58*(6), 1782–1797. https://doi.org/10.1109/jssc.2022.3198505

Navarro, E. d. M., Costa, N., & Pereira, Á. (2020). A Systematic Review of IoT Solutions for Smart Farming. *Sensors*, *20*(15), 4231. https://doi.org/10.3390/s20154231

Outferdine, F., Cherifi, K., Belkhiri, D., Bouachrine, B., & Ajaamoum, M. (2024). Implementation of a Low-Cost Intelligent Street Light System Using Internet of Things. *Indonesian Journal of Electrical Engineering and Computer Science*, *33*(3), 1387. https://doi.org/10.11591/ijeecs.v33.i3.pp1387-1396

Raza, U., Kulkarni, P., & Sooriyabandara, M. (2017). Low Power Wide Area Networks: An Overview. *Ieee Communications Surveys & Tutorials*, *19*(2), 855–873. https://doi.org/10.1109/comst.2017.2652320

Sanjeevi, P., Prasanna, S., Sivakumar, B., Gunasekaran, G., Alagiri, I., & Anand, R. V. (2020). Precision Agriculture and Farming Using Internet of Things Based on Wireless Sensor Network. *Transactions on Emerging Telecommunications Technologies*, *31*(12). https://doi.org/10.1002/ett.3978

Saraereh, O. A., Alsaraira, A., Khan, I., & Choi, B. J. (2020). A Hybrid Energy Harvesting Design for on-Body Internet-of-Things (IoT) Networks. *Sensors*, *20*(2), 407. https://doi.org/10.3390/s20020407

Shan, Y., Wang, H., & Zhang, C. (2022). Multinode Data Offloading for Urban Wireless Sensor Networks Based on Fog Computing: A Multiarmed Bandit Approach. *Security and Communication Networks*, *2022*, 1–17. https://doi.org/10.1155/2022/2965081

Sultania, A. K., Delgado, C., & Famaey, J. (2020). Enabling Low-Latency Bluetooth Low Energy on Energy Harvesting Batteryless Devices Using Wake-Up Radios. *Sensors*, *20*(18), 5196. https://doi.org/10.3390/s20185196

Ugwuanyi, S., Paul, G., & Irvine, J. (2021). Survey of IoT for Developing Countries: Performance Analysis of LoRaWAN and Cellular NB-IoT Networks. *Electronics*, *10*(18), 2224. https://doi.org/10.3390/electronics10182224

Valente, A., Silva, S., Duarte, D., Pinto, F. C., & Soares, S. (2020). Low-Cost LoRaWAN Node for Agro-Intelligence IoT. *Electronics*, *9*(6), 987. https://doi.org/10.3390/electronics9060987

Vijayan, D. S., Koda, E., Sivasuriyan, A., Winkler, J., Parthiban, D., Kumar, R. S., Jakimiuk, A., Osiński, P., Podlasek, A., & Vaverková, M. D. (2023). Advancements in Solar Panel Technology in Civil Engineering for Revolutionizing Renewable Energy Solutions—A Review. *Energies*, *16*(18), 6579. https://doi.org/10.3390/en16186579

Wong, K.-S., & Wan, T. (2019). Current State of Multicast Routing Protocols for Disruption Tolerant Networks: Survey and Open Issues. *Electronics*, *8*(2), 162. https://doi.org/10.3390/electronics8020162

Yadav, R., Manshahia, M. S., & Chaudhary, M. P. (2024). Optimizing IoT Networks in Smart Agriculture Using Probabilistic Models and Machine Learning Algorithms. *International Journal of Scientific Research in Science and Technology*, *11*(6), 196–204. https://doi.org/10.32628/ijsrst24116169

Zhang, Y., Abbas, H., & Sun, Y. (2019). Smart E-Commerce Integration With Recommender Systems. *Electronic Markets*, *29*(2), 219–220. https://doi.org/10.1007/s12525-019-00346-x.