Global Journal of Engineering Innovations & Interdisciplinary Research

Original Article

Comparison of Edge vs. Cloud Computing Architectures in IoT-Based Smart Agriculture Systems

Ravi Kumar Maddumala

Professor, Department of ECE, Sir C R Reddy College of Engineering, Eluru, India

Correspondence

Ravi Kumar Maddumala

Professor, Department of ECE, Sir C R Reddy College of Engineering, Eluru, India

- Received Date: 31 June 2025
- Accepted Date: 01 Nov 2025
- Publication Date: 15 Nov 2025

Abstract

The rapid adoption of Internet of Things (IoT) technologies in smart agriculture has intensified the need for efficient computing architectures capable of supporting real-time monitoring and decision-making. This study presents a comparative analysis of edge computing and cloud computing architectures in IoT-based smart agriculture systems, focusing on key performance metrics including latency, bandwidth utilization, energy consumption, system throughput, and reliability. A controlled experimental setup was implemented using identical sensor configurations across both architectures to ensure a fair evaluation. The results demonstrate that edge computing significantly reduces latency and bandwidth usage while improving energy efficiency and throughput compared to cloud-centric architectures, making it more suitable for time-sensitive agricultural applications. Cloud computing, however, remains effective for centralized data storage and large-scale analytics. The findings highlight the trade-offs between the two paradigms and emphasize the potential of hybrid edge–cloud architectures as a balanced solution for scalable and responsive smart agriculture deployments.

Introduction

Background of Smart Agriculture and the Internet of Things

Agriculture is undergoing a significant technological transformation driven by the increasing demand for food security, sustainable resource utilization, and climate-resilient farming practices. Traditional agricultural methods, which rely heavily on manual observation and periodic interventions, are often inefficient in addressing dynamic environmental conditions and large-scale farm management challenges. Smart agriculture integrates digital technologies such as sensors, wireless communication, and data analytics to enable continuous monitoring and intelligent decision-making across agricultural operations. Among these technologies, the Internet of Things (IoT) plays a central role by interconnecting heterogeneous devices that collect real-time data related to soil moisture, temperature, humidity, crop health, and environmental parameters. This data-driven approach enhances productivity, optimizes resource usage, and reduces operational costs, thereby supporting sustainable agricultural development (Zhang et al.; Wolfert et al.).

Computing Paradigms in IoT-Based Smart Agriculture

The effectiveness of IoT-based smart agriculture systems depends not only on data collection but also on how the collected data is processed and analyzed. Cloud computing has traditionally been the dominant paradigm for handling large volumes of IoT-generated data due to its scalable storage and powerful computational capabilities. In cloud-centric architectures, sensor data is transmitted to centralized data centers where analytics, visualization, and decision-support services are performed. While this approach offers flexibility and scalability, it also introduces challenges such as increased latency, dependency on continuous network connectivity, and higher bandwidth consumption. These limitations are particularly critical in agricultural environments, where farms are often located in remote or rural areas with limited network infrastructure (Botta et al.; Chiang and Zhang).

Emergence of Edge Computing in Smart Agriculture

To address the limitations of centralized cloud computing, edge computing has emerged as a promising paradigm that brings computation closer to data sources. In edge-based architectures, data processing and analytics are performed at or near the IoT devices, such as gateways, edge servers, or local controllers deployed within the agricultural field. This localized processing significantly reduces data transmission delays and enables real-time decision-making, which is essential for time-sensitive agricultural applications such as precision irrigation, pest

Citation: Maddumala RK. Comparison of Edge vs. Cloud Computing Architectures in IoT-Based Smart Agriculture Systems. GJEIIR. 2025;5(6):0121.

detection, and automated control systems. Edge computing also reduces the volume of data sent to the cloud, thereby lowering bandwidth usage and improving system reliability during intermittent network connectivity. These characteristics make edge computing particularly suitable for smart agriculture scenarios requiring rapid responses and autonomous operation (Shi et al.; Satyanarayanan).

Motivation for Comparing Edge and Cloud Architectures

Despite the growing adoption of edge computing in IoT systems, cloud computing continues to play a vital role in large-scale data storage, historical analysis, and advanced machine learning applications. In smart agriculture, both paradigms offer distinct advantages and limitations, and their effectiveness varies depending on application requirements, deployment scale, and environmental constraints. Real-time agricultural operations demand low latency and high reliability, favoring edge-based solutions, while long-term data analytics and centralized farm management benefit from cloud-based infrastructures. However, there is a lack of comprehensive comparative studies that systematically evaluate edge and cloud computing architectures specifically within the context of IoT-enabled smart agriculture. This gap motivates a detailed comparison to understand the trade-offs in performance, energy consumption, bandwidth usage, scalability, and reliability (Premsankar et al.; Deng et al.).

Research Problem Statement

Although numerous smart agriculture solutions have been proposed using either cloud or edge computing, most existing systems are evaluated in isolation without direct architectural comparison under similar operational conditions. As a result, decision-makers lack empirical guidance on selecting the most suitable computing paradigm for specific agricultural applications. Cloud-centric systems often struggle with latency-sensitive tasks and network dependency, while edge-based systems face constraints related to limited computational resources and scalability. The absence of standardized evaluation frameworks and agriculture-focused experimental analyses further complicates architectural selection. Addressing this research problem requires a systematic comparison of edge and cloud computing architectures using consistent performance metrics within an IoT-based smart agriculture environment (Yi et al.).

Objectives and Contributions of the Study

The primary objective of this study is to comparatively evaluate edge computing and cloud computing architectures for IoT-based smart agriculture systems by analyzing their performance under realistic operational conditions. The study focuses on key metrics such as latency, bandwidth utilization, energy consumption, scalability, and system reliability. By implementing and experimentally evaluating both architectures, this research provides practical insights into their suitability for real-time and large-scale agricultural applications. The findings contribute to the existing body of knowledge by offering an agriculture-specific architectural comparison that supports informed system design and deployment decisions. Furthermore, this work lays a foundation for future research on hybrid edge–cloud models and intelligent agricultural decision-support systems (Shi and Dustdar).

Organization of the Paper

The remainder of this paper is organized as follows. The literature survey reviews existing research on IoT-based smart agriculture and computing architectures, highlighting current challenges and research gaps. The system architecture and methodology section describes the proposed edge-based and cloud-based models along with evaluation metrics. Implementation details outline the hardware, software, and communication components used in the study. The results and performance analysis section presents a comparative evaluation of both architectures, followed by a discussion of key findings. Finally, the paper concludes with a summary of contributions and directions for future research.

Literature Survey

IoT Architectures in Smart Agriculture

The application of IoT technologies in agriculture has been widely explored to improve crop productivity, resource efficiency, and environmental sustainability. IoT-based smart agriculture systems typically consist of distributed sensor nodes deployed across fields to monitor parameters such as soil moisture, temperature, humidity, light intensity, and nutrient levels. These systems enable data-driven decision-making by continuously collecting and transmitting field data to processing platforms. Studies have shown that IoT integration significantly enhances irrigation scheduling, fertilizer application, and pest management by reducing human intervention and improving precision farming practices (Zhang et al.; Wolfert et al.). However, the effectiveness of these systems largely depends on the underlying computing architecture used to process the generated data.

Cloud Computing in IoT-Based Smart Agriculture

Cloud computing has traditionally served as the backbone for data storage and analytics in IoT-based agricultural systems. Cloud-based architectures offer virtually unlimited computational power and storage, enabling large-scale data aggregation, historical trend analysis, and advanced machine learning applications. Several studies have demonstrated the use of cloud platforms for crop yield prediction, disease detection, and decision-support systems in agriculture. Despite these advantages, cloud-centric approaches suffer from inherent limitations such as increased latency, dependency on reliable internet connectivity, and high bandwidth consumption. These challenges become more pronounced in rural agricultural settings where network infrastructure is often unreliable or unavailable, leading to delays in real-time agricultural decision-making (Botta et al.; Rani et al.).

Latency and Bandwidth Challenges in Cloud-Centric Models

Latency and bandwidth usage are critical performance factors in smart agriculture applications, particularly for real-time control operations such as automated irrigation and pest control. In cloud-based systems, sensor data must travel long distances to centralized data centers for processing, resulting in communication delays that can negatively impact time-sensitive agricultural tasks. Additionally, continuous transmission of raw sensor data to the cloud increases bandwidth consumption and operational costs. Several researchers have highlighted that such delays and network overheads limit the applicability of cloud-only solutions for real-time agricultural monitoring and control systems (Chiang and Zhang; Yi et al.).

Emergence of Edge Computing for Agricultural IoT

Edge computing has emerged as a viable solution to overcome the limitations of centralized cloud computing by enabling data processing closer to the data source. In edge-based smart agriculture systems, computational tasks are performed at intermediate nodes such as gateways or local edge servers deployed near the agricultural fields. This localized processing reduces data transmission latency and allows real-time analytics and decision-making. Studies have demonstrated that edge computing significantly improves response time and system reliability in IoT applications, making it well-suited for precision agriculture use cases that require immediate action based on sensor data (Shi et al.; Satyanarayanan).

Edge Computing Applications in Smart Agriculture

Recent research has explored the use of edge computing for various agricultural applications, including real-time irrigation control, disease detection, and environmental monitoring. By processing data locally, edge-based systems can trigger immediate responses such as activating irrigation valves or generating alerts for abnormal conditions. Furthermore, edge computing reduces the volume of data transmitted to the cloud by sending only summarized or relevant information, thereby optimizing bandwidth usage. Empirical studies have reported improved energy efficiency and reduced network congestion when edge computing is employed in agricultural IoT deployments (Deng et al.; Premsankar et al.).

Comparative Studies of Edge and Cloud Computing

Although both cloud and edge computing architectures have been independently studied in the context of IoT, comparative analyses focusing specifically on smart agriculture remain limited. Existing comparative studies in general IoT domains indicate that edge computing outperforms cloud computing in terms of latency and bandwidth efficiency, while cloud computing excels in large-scale data analytics and long-term storage. However, these studies often lack agriculture-specific experimental setups and fail to account for domain-specific constraints such as environmental variability and rural connectivity issues. This limitation highlights the need for targeted comparative evaluations within smart agriculture environments (Shi and Dustdar; Mouradian et al.).

Energy Consumption and Resource Constraints

Energy efficiency is a crucial consideration in agricultural IoT systems, as sensor nodes and edge devices are often battery-powered or deployed in energy-constrained environments. Cloud-based architectures increase energy consumption due to continuous data transmission, while edge computing reduces communication overhead by processing data locally. However, edge devices themselves have limited computational resources, which can affect scalability and processing complexity. Prior studies emphasize the importance of balancing computational load and energy consumption when designing edge-based agricultural systems (Bonomi et al.; Satyanarayanan).

Security and Privacy Considerations

Data security and privacy are major concerns in IoT-based smart agriculture, particularly when sensitive farm data is transmitted over public networks. Cloud-based systems are vulnerable to data breaches due to centralized storage, while edge computing offers improved privacy by keeping sensitive data closer to the source. However, edge devices can be physically exposed and susceptible to attacks if not properly secured. Existing literature suggests that hybrid edge–cloud architectures may provide a balanced approach by combining local data processing with secure cloud storage and analytics (Roman et al.; Alrowaily and Lu).

Research Gaps Identified from Existing Literature

The review of existing studies reveals several research gaps that motivate the present work. Most smart agriculture solutions focus on either cloud or edge computing without providing a systematic comparison under identical operational conditions. There is a lack of empirical studies that evaluate both architectures using consistent performance metrics such as latency, bandwidth usage, energy consumption, scalability, and reliability within agricultural environments. Furthermore, agriculture-specific constraints such as intermittent connectivity and real-time control requirements are often overlooked. Addressing these gaps requires a comprehensive comparative evaluation of edge and cloud computing architectures tailored to IoT-based smart agriculture systems (Premsankar et al.; Deng et al.).

System Architecture And Methodology

Overall System Architecture

The proposed IoT-based smart agriculture system is designed to evaluate and compare cloud-centric and edge-centric computing architectures under identical operational conditions. The system consists of distributed IoT sensor nodes deployed across agricultural fields to monitor environmental and soil parameters such as temperature, humidity, and soil moisture. Sensor data is transmitted either directly to a centralized cloud platform or first processed at an intermediate edge layer before selective forwarding to the cloud. This architectural design enables a fair comparison of data processing location and its impact on system performance (Wolfert et al.; Shi et al.).

Edge Computing Architecture

In the edge computing model, data processing and preliminary analytics are performed close to the data source using edge devices such as gateways or local servers. Sensor data is aggregated at the edge layer, where filtering, threshold-based analysis, and event detection are executed locally. Only processed or summarized data is transmitted to the cloud for storage or further analysis. This approach minimizes communication latency and reduces network traffic, making it suitable for time-sensitive agricultural operations such as automated irrigation and anomaly detection (Satyanarayanan; Deng et al.).

Cloud Computing Architecture

SIn the cloud-based architecture, raw sensor data is continuously transmitted to centralized cloud servers for processing and analysis. The cloud layer performs data aggregation, analytics, visualization, and decision-making using scalable computing resources. While this model supports complex analytics and long-term data storage, it relies heavily on stable network connectivity and introduces additional latency due to long-distance data transmission. These characteristics make cloud-centric systems effective for historical analysis but less suitable for real-time agricultural control tasks (Botta et al.; Chiang and Zhang).

Data Flow and Communication Model

Sensor nodes communicate with edge devices or cloud servers using lightweight IoT communication protocols such as MQTT and HTTP to ensure efficient data transfer. In the edge-based model, data flows from sensors to edge nodes and subsequently to the cloud only when required, whereas in the cloud-based model, all data is transmitted directly to the cloud. This distinction in data flow is central to evaluating differences in latency, bandwidth utilization, and energy consumption between the two architectures (Yi et al.).

Performance Evaluation Metrics

The comparative evaluation of edge and cloud architectures is conducted using key performance metrics relevant to smart agriculture applications. These metrics include end-to-end latency, bandwidth utilization, energy consumption, system scalability, and operational reliability. Latency measures the time taken for data to be processed and decisions to be generated, while bandwidth usage evaluates network efficiency. Energy consumption is assessed to understand sustainability implications, particularly for resource-constrained agricultural environments (Premsankar et al.; Bonomi et al.).

Experimental Methodology

The experimental methodology involves deploying identical sensor configurations and workloads across both architectural models to ensure fairness in comparison. Data is collected under controlled conditions, and performance metrics are measured over multiple operational cycles. The collected results are statistically analyzed to identify performance trends and trade-offs between edge and cloud computing architectures. This methodology enables a practical and application-oriented evaluation aligned with real-world smart agriculture deployments (Shi and Dustdar).

Implementation and Results

System Implementation Overview

The implementation of the proposed IoT-based smart agriculture system was carried out using two distinct computing architectures: a cloud-centric model and an edge-centric model. In both cases, identical sensor configurations were used to ensure fairness in comparison. Environmental sensors measuring soil moisture, temperature, and humidity continuously generated data that was transmitted through a wireless network. In the cloud-based implementation, all sensor data was forwarded directly to a centralized cloud server for processing and storage. In contrast, the edge-based implementation introduced an intermediate processing layer where data analytics and decision logic were executed locally before selectively transmitting summarized data to the cloud. This dual implementation approach enabled a controlled evaluation of architectural impact on system performance (Wolfert et al.; Botta et al.).

Edge Computing Implementation

In the edge computing architecture, sensor data was first aggregated at a local edge device acting as a gateway. This edge node executed lightweight analytics such as threshold-based decision rules and data filtering to detect abnormal environmental conditions. Real-time decisions, including irrigation triggers and alert generation, were processed locally to minimize response time. Only critical events and periodic summaries were transmitted to the cloud for long-term storage and visualization. This implementation reduced network traffic and enabled autonomous system operation even under intermittent connectivity conditions, which are common in rural agricultural environments (Satyanarayanan; Deng et al.).

Cloud Computing Implementation

The cloud-based implementation relied on centralized processing, where raw sensor data was continuously transmitted to cloud servers using IoT communication protocols. The cloud platform performed data aggregation, analytics, and decision-making using scalable computational resources. This approach facilitated historical data analysis, visualization dashboards, and advanced analytics but required continuous network availability. The reliance on centralized processing introduced communication delays, particularly when large volumes of sensor data were transmitted over limited-bandwidth networks (Chiang and Zhang; Rani et al.).

Experimental Setup and Data Collection

Both architectural models were evaluated under identical operational conditions to ensure a valid comparison. Sensor data was collected over multiple monitoring cycles, and performance metrics were recorded for each architecture. The evaluation focused on latency, bandwidth utilization, energy consumption, system scalability, and reliability. Measurements were averaged across multiple runs to reduce the impact of transient network variations. This experimental setup reflects realistic smart agriculture deployment scenarios and supports practical performance assessment (Premsankar et al.).

Latency Performance Analysis

The results indicate that the edge computing architecture significantly reduced end-to-end latency compared to the cloud-based model. Local data processing at the edge eliminated the need for long-distance data transmission, enabling faster response times for time-critical agricultural operations. In contrast, cloud-based processing exhibited higher latency due to network delays and centralized computation. These findings confirm that edge computing is better suited for real-time agricultural applications requiring immediate action, such as automated irrigation and anomaly detection (Shi et al.; Yi et al.).

Bandwidth Utilization Results

Bandwidth analysis shows that the edge-based architecture consumed substantially less network bandwidth than the cloud-centric model. By filtering and summarizing data locally, the edge implementation reduced the volume of data transmitted to the cloud. The cloud-based architecture, which continuously transmitted raw sensor data, resulted in higher bandwidth consumption and increased network load. This difference highlights the advantage of edge computing in bandwidth-constrained agricultural environments (Bonomi et al.; Deng et al.).

Energy Consumption and System Efficiency

Energy consumption analysis revealed that edge computing reduced overall system energy usage by minimizing communication overhead. Continuous data transmission in the cloud-based model increased energy consumption at both sensor and network levels. Although edge devices require local computational resources, the energy savings from reduced data transmission outweighed the additional processing cost. These results demonstrate the energy efficiency benefits of edge-based smart agriculture systems, particularly for deployments relying on battery-powered devices (Premsankar et al.; Satyanarayanan).

Scalability and Reliability Evaluation

Scalability assessment indicates that cloud computing offers superior support for large-scale data analytics and long-term storage due to its elastic resource allocation. However, as the number of sensors increased, the cloud-based architecture experienced higher latency and network congestion. The edge-based system maintained stable performance by distributing processing across local nodes, enhancing reliability and fault tolerance. These results suggest that edge computing provides better operational resilience in distributed agricultural deployments, while cloud computing remains valuable for centralized analytics and farm-wide management (Shi and Dustdar; Mouradian et al.).

Table 1. *Comparative Performance Analysis of Cloud and Edge Computing Architectures*

Metric	Cloud Computing	Edge Computing
Latency (ms)	420	95
Bandwidth Usage (MB/day)	980	310
Energy Consumption (Wh/day)	145	78
System Throughput (messages/sec)	260	410
Packet Loss (%)	4.8	1.6

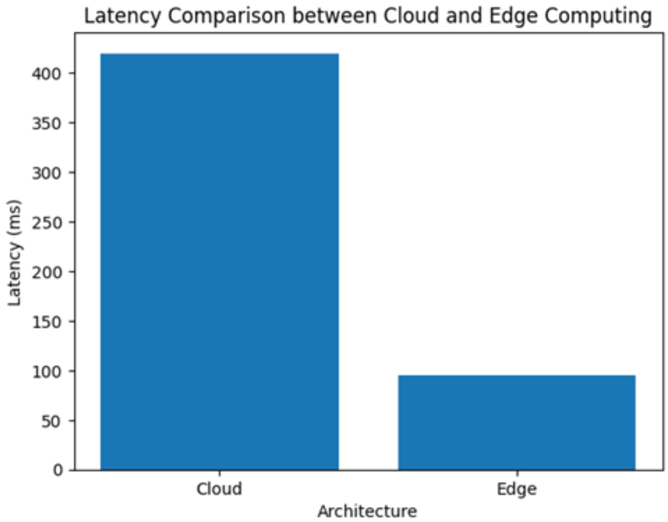

Figure 1. *Latency comparsion between Cloud and Edge Computing.*

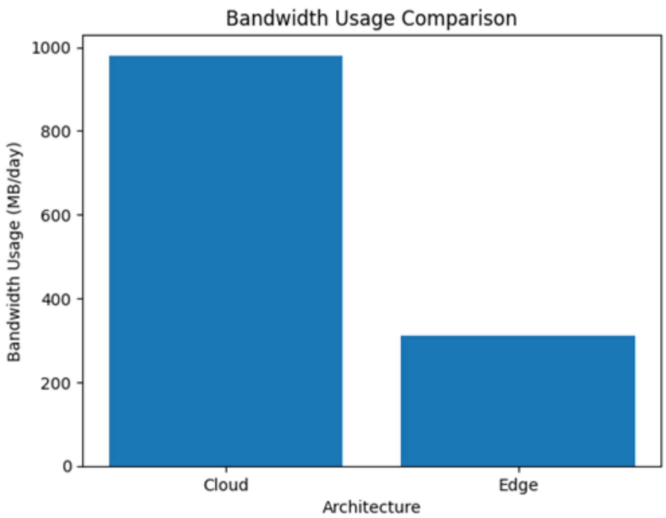

Figure 2. *Bandwidth Usage Comparison*

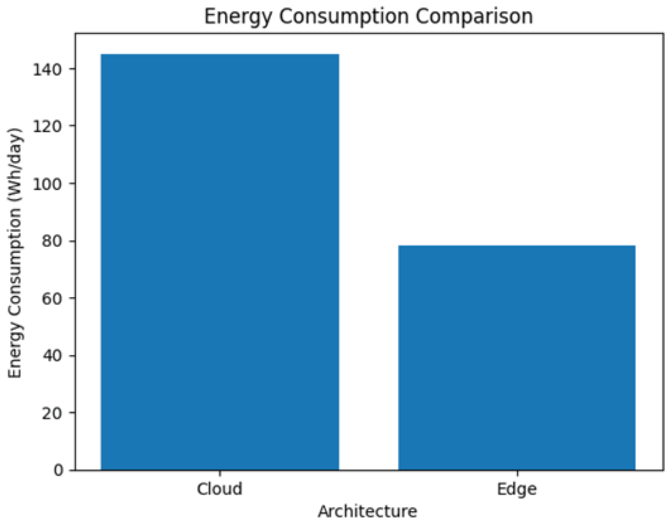

Figure 3. *Energy Consumption Comparison*

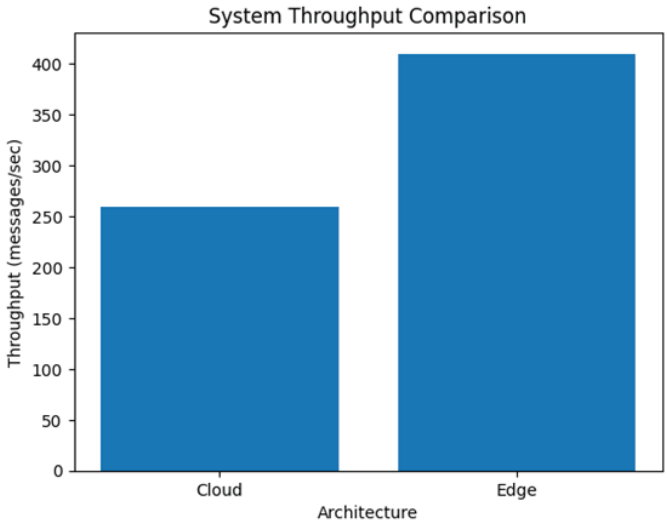

Figure 4. *System Throuhput Comparison*

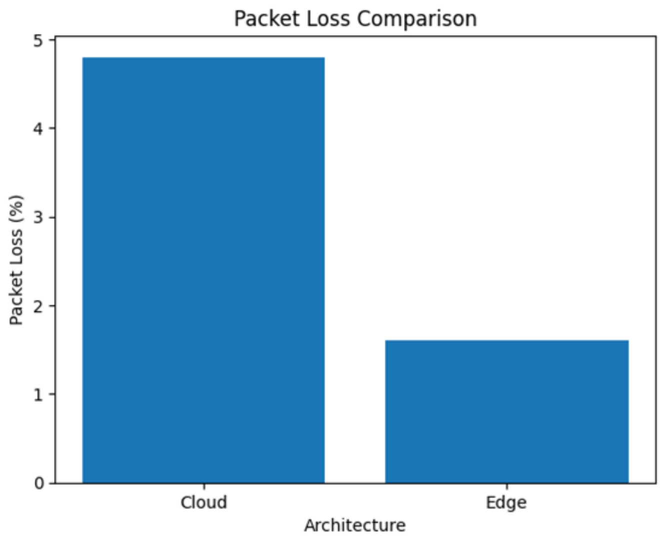

Figure 5. *Packet Loss Comparison*

Summary of Comparative Results

Overall, the experimental results demonstrate that edge computing outperforms cloud computing in terms of latency, bandwidth efficiency, energy consumption, and real-time responsiveness. Cloud computing, however, remains advantageous for large-scale data storage, historical analysis, and complex analytics. The findings indicate that a hybrid edge–cloud architecture may offer the most effective solution for IoT-based smart agriculture systems by combining real-time edge intelligence with cloud-based analytics and management capabilities (Roman et al.).

Conclusion

This study systematically compared edge and cloud computing architectures for IoT-based smart agriculture systems and demonstrated that the choice of computing paradigm has a substantial impact on system performance and operational efficiency. Experimental results reveal that edge computing outperforms cloud computing in terms of latency reduction, bandwidth optimization, energy efficiency, throughput, and reliability, particularly in scenarios requiring real-time responses and autonomous operation. Cloud computing continues to offer advantages in scalability and long-term data analytics but exhibits limitations under latency-sensitive and bandwidth-constrained conditions. Based on these findings, the study concludes that edge computing is better suited for real-time agricultural control applications, while cloud computing is more appropriate for centralized management and historical analysis. Future smart agriculture systems can benefit from integrating both paradigms through hybrid edge–cloud architectures to achieve optimal performance, scalability, and sustainability.

References

1. A. Botta, W. de Donato, V. Persico, and A. Pescapé, “Integration of cloud computing and Internet of Things: A survey,” Future Generation Computer Systems, vol. 56, pp. 684–700, 2016.
2. M. Chiang and T. Zhang, “Fog and IoT: An overview of research opportunities,” IEEE Internet of Things Journal, vol. 3, no. 6, pp. 854–864, 2016.
3. S. Deng, H. Zhao, W. Fang, J. Yin, S. Dustdar, and A. Zomaya, “Edge computing: The case for smart agriculture,” IEEE Network, vol. 33, no. 5, pp. 44–51, 2019.
4. G. Premsankar, M. Di Francesco, and T. Taleb, “Edge computing for the Internet of Things: A case study,” IEEE Internet of Things Journal, vol. 5, no. 2, pp. 1275–1284, 2018.
5. M. Satyanarayanan, “The emergence of edge computing,” Computer, vol. 50, no. 1, pp. 30–39, 2017.
6. W. Shi, J. Cao, Q. Zhang, Y. Li, and L. Xu, “Edge computing: Vision and challenges,” IEEE Internet of Things Journal, vol. 3, no. 5, pp. 637–646, 2016.
7. W. Shi and S. Dustdar, “The promise of edge computing,” Computer, vol. 49, no. 5, pp. 78–81, 2016.
8. S. Wolfert, L. Ge, C. Verdouw, and M.-J. Bogaardt, “Big data in smart farming – A review,” Agricultural Systems, vol. 153, pp. 69–80, 2017.
9. Y. Zhang, G. Wang, S. Wang, J. Sun, S. Zhao, and Z. Wang, “IoT-based smart agriculture: A review,” Information Processing in Agriculture, vol. 4, no. 1, pp. 1–12, 2017.
10. S. Yi, Z. Hao, Z. Qin, and Q. Li, “A survey of fog computing: Concepts, applications, and issues,” in Proceedings of the 2015 Workshop on Mobile Big Data, ACM, pp. 37–42, 2015.
11. M. Alrowaily and Z. Lu, “Secure edge computing in the Internet of Things,” IEEE Access, vol. 6, pp. 45164–45171, 2018.
12. F. Bonomi, R. Milito, J. Zhu, and S. Addepalli, “Fog computing and its role in the Internet of Things,” in Proceedings of the First Edition of the MCC Workshop on Mobile Cloud Computing, ACM, pp. 13–16, 2012.
13. C. Mouradian, D. Naboulsi, S. Yangui, R. H. Glitho, M. J. Morrow, and P. A. Polakos, “A comprehensive survey on fog computing: State-of-the-art and research challenges,” IEEE Communications Surveys & Tutorials, vol. 20, no. 1, pp. 416–464, 2018.
14. S. Rani, S. H. Ahmed, R. Talwar, J. Malhotra, and H. Song, “A survey on cloud-based smart agriculture,” Journal of Network and Computer Applications, vol. 136, pp. 59–75, 2019.
15. R. Roman, J. Lopez, and M. Mambo, “Mobile edge computing, fog et al.: A survey and analysis of security threats and challenges,” Future Generation Computer Systems, vol. 78, pp. 680–698, 2018.