The Role of IoT and Guidance Systems in Cost-Effective Precision Agriculture: A Focus on Irrigation and Fertilization

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Abstract

The integration of Internet of Things (IoT) technology in precision agriculture has radically transformed agricultural practices, significantly contributing to increased efficiency and productivity. This paper aims to examine the application of IoT technologies through advanced guidance systems to assess their impact on cost management and improved use of agricultural resources. For this, the study used iFogSim Simulator to simulate the application of these technologies and systems. By deploying these systems, farmers can achieve higher accuracy in field operations, which positively reflects on reducing operational costs and increasing yields. The results indicate that the adoption of IoT-enabled guidance systems contributed to significantly reducing irrigation and fertilization costs by up to 25%, as these systems were able to accurately monitor moisture levels and soil requirements, which led to reducing water and fertilizer waste and achieving optimal use of them. In addition, the data collected from different agricultural environments helped improve irrigation and fertilization scheduling, which reduced labor interventions, reduced operating costs up 7%, and increased the efficiency of agricultural operations. The results showed a significant reduction in labor and agricultural input costs up to 15%, along with improved crop quality and productivity. This study highlights the great potential of the Internet of Things to support more sustainable and economical agricultural practices by providing a comprehensive cost-benefit analysis that enhances the adoption of these new technologies. The study recommends to apply IoT and guidance-based precision system on a real field experiment on sugar or wheat crops and comparing the simulation results with actual results.

Keywords: precision agriculture; guidance systems; fertilization; irrigation; IoT

دور إنترنت الأشياء وأنظمة الإرشاد في الزراعة الدقيقة الفعالة من حيث التكلفة: بالتطبيق على الري والتسميد

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مستخلص الدراسة

أحدث دمج تقنية إنترنت الأشياء (IoT) في الزراعة الدقيقة تحولاً جذرياً في الممارسات الزراعية، مما ساهم بشكل كبير في زيادة الكفاءة والإنتاجية. تهدف هذه الورقة إلى دراسة تطبيق تقنيات إنترنت الأشياء من خلال أنظمة إرشاد متقدمة لتقييم أثرها على إدارة التكاليف وتحسين استخدام الموارد الزراعية. ومن خلال نشر هذه الأنظمة (أي أنظمة الإرشاد)، يمكن للمزارعين تحقيق دقة أعلى في العمليات الحقلية، بما ينعكس إيجاباً على خفض تكاليف التشغيل وزيادة الانتاجية. ولتحقيق ذلك، استخدمت الدراسة iFogSim Simulator لمحاكاة تطبيق هذه التقنيات والأنظمة. وتشير النتائج إلى أن اعتماد أنظمة الإرشاد المدعومة بإنترنت الأشياء ساهم في خفض تكاليف الري والتسميد بنسبة تصل إلى 25%، حيث تمكنت هذه الأنظمة من رصد مستويات الرطوبة ومتطلبات التربة بدقة، مما أدى إلى تقليل هدر المياه والأسمدة وتحقيق الاستخدام الأمثل لها. بالإضافة إلى ذلك، ساعدت البيانات التي تم جُمعت من بيئات زراعية مختلفة في تحسين جدولة الري والتسميد، مما قلل من تدخلات العمالة، وخفّض تكاليف التشغيل بنسبة تصل إلى 7%، وزاد من كفاءة العمليات الزراعية. كما أظهرت النتائج انخفاضاً كبيراً في تكاليف العمالة والمدخلات الزراعية بنسبة تصل إلى 15%، إلى جانب تحسين جودة المحاصيل وإنتاجيتها. وتسلط هذه الدراسة الضوء على الإمكانات الكبيرة لإنترنت الأشياء لدعم ممارسات زراعية أكثر استدامة واقتصادية من خلال توفير تحليل شامل للتكلفة والعائد، بما يعزز اعتماد هذه التقنيات الجديدة. توصي الدراسة بتطبيق إنترنت الأشياء ونظام الدقة المبني على التوجيه على تجربة ميدانية حقيقية على محاصيل السكر أو القمح ومقارنة نتائج المحاكاة بالنتائج الفعلية.

كلمات مفتاحية: الزراعة الدقيقة؛ أنظمة الإرشاد؛ التسميد؛ الري؛ إنترنت الأشياء

1. Introduction

The growing global population and the growing demand for food have put less pressure on agriculture to produce more with less cost (Xu et al., 2024). Innovations in accurate irrigation and fertilization have emerged to meet this requirement by increasing the dividend and the quality of the crop by adapting the use of resources and reducing the environmental impact (Xing & Wang, 2024). For example, accurate watering "distributes multiple crops for drop" and accurate fertilizer placement can double the nutrients absorbed by plants, showing how to reduce targeted incidence (Musumba et al., 2017). In this context, modern agriculture is seeking cost-effect techniques: Guidance and automation technologies can cut costs and work requirements. In fact, the tractor guide system on small farms can achieve economic and environmental savings - low costs are often translated into increased profits and high returns (Khanna and Kaur, 2019). This factor - the need to increase productivity, environmental and economic efficiency - inspires a change to accurate agriculture and guidance systems.

Water, fertilizers and pesticides are used equally in traditional agricultural practices, which ignore field variability. This "one-set-all" approach often leads to wasted input and unexpectedness in the crop performance. Disable use of water and nutrients is common, resulting in financial loss and environmental decline (Xing & Wang, 2024). For example, fields treated with carpet fertilizer plans often experience nutrient leaching and runoff, while crops in parts of the area can receive insufficient inputs. In addition, traditional methods are usually labor-intensive and reactive: farmers depend on manual monitoring and planning instead of real-time data. Such practice not only increases operating costs, but also reduces soil health and water quality over time. On the other hand, data-driven accurate techniques promise to remove these limitations by adjusting the inputs for real crop needs.

Modern precision system uses advanced technologies to convert data to customized agricultural functions. Large benefits include:

- ***Sensors and IoT networks:*** Earth moisture checks, crop sensors and weather stations collect real -time data on the condition of the station area. For example, soil moisture sensors can automatically trigger watering when the levels fall, reduce water use without human intervention (Soussi et al., 2024). Smart sensor networks thus allow farmers to continuously monitor and manage crops.

- ***Geospatial imaging (satellite/drone/GIS):*** High-resolution and high-resolution satellite and drone images, combined with GPS mapping, create wide field variability maps (Xing & Wang, 2024; Soussi et al., 2024). These maps reveal the difference in soil types, nutritional status and crop strength on a farm. Convertible Rate Technology (VRT) then uses this information to adjust seeds, fertilizers and pesticides. For example, fertilizer sponsored GPS can use more nutrients in low zones and was already enough, adaptation of entry use (Xing and Wang, 2024).
- ***Data analysis and machine learning:*** Large versions of sensors and image data are processed by AI and analysis platforms to produce decision support. Advanced algorithms can predict crop needs and suggest accurate intervention. These systems enable timely and localized control functions by explaining the pattern (for example, dried stress or deficiencies in nutrients). Improvement in the result is better in making decisions: Farmers receive action-rich recommendations instead of relying only on experience or average (Soussi et al., 2024).
- ***Guidance and automation:*** GPS-competent guidance system with optimal routes with system stools and equipment, improvement of accuracy and reduces the operator's fatigue (Khanna and Kaur, 2019). Automatic control and implementation checks ensure that seeding, spraying and tillage are followed by accurate tracks and prices. This spatial precision not only reduces labor and overlap, but also increases operational efficiency and stability. Research has shown that GPS-based guidance can significantly promote dividends and reduce incidence by maintaining accurate control of agricultural operations (Khanna and Kaur, 2019).
- ***Resource use efficiency:*** Together, these innovations improve dramatically input efficiency. Exact watering and fertility technologies ensure water and nutrients that reduce the damage and correspond to the crop of crop. As a comprehensive review

notes, accurate water and fertilizer applications provide sufficient benefits for permanent agricultural practices by “improving crops, increasing resource efficiency and reducing environmental impact” (Khanna & Kaur, 2019). In practice, it reports that accurate cost development (fast cuts and chemical applications up to a large percentage while it is low to increase the growing water use and chemical use up to a large percentage of quality and organic footprints.

Based on insights mentioned-above, major study questions include:

- How can agricultural costs be reduced by improving crop quality?
- Can IoT technologies and guidance systems increase the decision for farmers?
- Does the guidance system effectively reduce input waste (e.g., water and fertilizer)?

The purpose of these questions is to examine whether the integration of accurate technologies can provide average financial benefits and productivity benefits. For example, research will be investigated whether sensor networks and data analysis of real-time can help farmers make more accurate management decisions. It will also evaluate the effectiveness of GPS-oriented equipment to reduce overlap and preserve resources. By addressing these questions, the study tries to determine how the exact agricultural and guidance system can reduce costs simultaneously and promote crop performance.

The remainder of the paper is organized as follows. Section 2 considers current relevant work. Section 3 describes the materials and methods of the study. Section 4 shows the study’s data. The results of the study are discussed in section 5. The results are discussed in section 5.

2. Related Work

Integration of IoT technologies into accurate agriculture has given rise to more data-driven watering and fertilization practices. Recent reviews have noted that the IoT competition system distributes wireless sensor networks (WSN) to collect real-time data on soil moisture, weather and crop health (Benzaouia et al., 2023; Abdelmonim et al., 2025). This connection emphasizes accurate watering by enabling data -driven decisions in time to adapt water use. Abdelmonim et al. (2025) explains how IoT architecture (including low-power and cloud integration protocols) how to form the basis for smart irrigation control. Empirical studies confirm these benefits: For example, Meriç (2025) stated that an IoT-based drip irrigation system (using wireless soil sensors and cloud compounds) received a dividend of .235.2% less water than a traditional ETC-based plan .12.1% more. Such results show that IoT sensing can significantly improve the efficiency of resource use in irrigation planning.

Many studies have expanded this by creating an irrigation planning system run by the Internet of Things. Many people use matriculation potential monitor or soil moisture sensors to start watering. By using a WSN of soil tensiometers in Loam soil, Jabro et al. (2020) Automatic planning by setting irrigation thresholds of 50% plant water. Similarly, low-cost ZigBee-based sensor nodes for dripping irrigation control and soil moisture has been field-tested, according to Meriç (2025). Other methods change irrigation planning by combining the sensory response with machine learning or weather forecast. However, Meriç (2025) notes that most of the IoT watering research uses general developmental boards (such as Arduino and Raspberry Pi) and focuses only on moisture, often leaving system streams or pressure data. In particular, important parameters such as line pressure and flow rate are reduced. This suggests the requirement for more extensive IoT watering platforms that include several hydrological measurements for actual accurate planning.

IoT has also been used for fertilization control. The sensor networks that monitor the soil's nutrients can conduct variable fertilizer doses. Musa et al. (2024) undergo several WSN implementation of NPK sensors, indicating that the monitoring of nitrogen, phosphorus and potassium becomes possible for precise nutritional control. Other functions link IoT watering with the control of nutrients. For instance, Meriç et al. (2025) Describe a multi-parameter IoT system measuring soil moisture, salinity, electric conductivity, pH and NPK with AI-driven recommendations for irrigation and fertilization. In practice, IoT fertilization controllers use sensor data to plan fertilizer injections through watering water. Some studies shed light on this: For example, an IoT fertilization prototype confirmed that pressure feeling is important for the production of irrigation systems before the distribution of nutrition. In total, however, several reported systems treat individual watering and fertilization, indicating a difference in integrated fertility solutions that adapt the fertilizer rate for soil and plant conditions in real-time.

These IoT systems are expanded with guidance and variable-rate technology, which allows the supply of accurate water and nutrients. Farm equipment can follow the exact area's routes for GPS/GNSS-based auto-siblings and mapping systems, which reduce overlap and enable site-specific operations. Modern centers change water production based on field maps using GNSS guidance for modern centers and linear irrigation systems Variable irrigation (VRI). This concept is extended to fertilizers and seeds through variable application (VRA). For example, Abdulla and Nafchi (2024) created a secluded GNSS-based VRA controller, which uses NCOD on board to dynamically modifying fertilizer/as speed dynamically with centimeters accuracy on the fly. Such systems explain how cheap microcontroller platforms (e.g., Raspberry Pi) can be linked to GNSS and motorized stations to enable accurate fertilization and watering without costly ownership. In general, integration of IoT sensor data with GNSS-directed VRA machines is an important promotion of accurate water and nutritional management in modern precision agriculture.

In spite of these advancements, significant gaps remain. Mary (2025) notes that most of the existing IoT watering solutions focus narrowly on soil moisture and ignore other hydraulic parameters. Similarly, while guidance equipment exists, they are often independent of sensor reactions on the aircraft for watering/fertility control. In fertilization, some systems automate fertilizer based on real-time data. In short, an integrated, affordable IoT platform that combines multi-sensor monitoring (humidity, flow, pressure, nutrients) with GPS for over control, is largely underdeveloped. To address these deficiencies is the inspiration for the current study, which aims to provide a cost-effective IoT-oriented solution for accurate irrigation and fertilization control.

3. Materials and Methods

3.1 Case Study

Sudan’s dry climate makes watering needed for large crops such as sugar cane and wheat. In fact, watering uses more than 96% of Sudan's indigo water distribution (Fanack Water, 2021). However, critical watering and the use of input uses serious problems. Non-form watering or fixed planned water can lead to more watering in parts of the area, which can cause water logging, nutrient for leaching and salt water (Bayabil et al., 2020). Excessive use of water and fertilizers destroys resources and increases pumping and chemical costs. Similarly, uncontrolled insects and outbreaks of disease regularly reduce dividends (20-40 percent) (Wang et al., 2024). Farmers often fight pests with heavy pesticides, but excessive spraying causes environmental pollution, harmful remains and pesticides resistance (Wang et al., 2024). In summary, Kassala producers stand for water shortages, soils and pests that require more accurate control. It has been found that it has been found that it is shown that it is using agricultural-driven, site-specific interventions to adapt, promote productivity and reduce environmental impacts.

The case study has a three-layer architecture - Edge/IoT, Fog and Cloud for monitoring and control of irrigation, fertilization and insect handling.

- ***Edge/IoT layer:*** This field layer includes sensors and actuators laid out in the field. Soil sensors (for example, volumetric moisture tests) measure real-time water content so that the system can determine the optimal irrigation time and volume (Mansoor et al., 2025). Additional environmental sensors (e.g. temperature, humidity and nutritional sensors) can measure the Earth’s pH or plant tension. Damage control monitoring can be used through a camera-heard network or mobile vision units. Actuators include irrigation pumps, valves and syringes (for fertilizers or pesticides). These units communicate wirelessly (e.g. via LoRa or Wi-Fi) at a local gateway. In summary, the edge/IoT layer collects continuous agricultural data and bears the control command.

- ***Fog Layer:*** Fog node is a local data processing hub (e.g. an edge server or industrial PC) located near the farm. This sensor collects data and runs real-time decisions algorithms (Singh et al., 2025). By processing the data if the data compresses the fog the node filter and the information, reduces the bandwidth in the cloud and improves the response time. For example, it uses the threshold logic for watering: to compare soil moisture from 40% setpoint and free up “pump on” or “pump off” then, compare soil moisture. Because the fog technique is physically close to the sensor, the low-lite control actions and continuous operation enables, even though the internet connection is intermittent (Singh et al., 2025).

- ***Cloud Layer:*** Cloud Component provides external data storage, advanced analyzes and user interface. It receives data collected from the fog layer and stores historical records for long-term analysis and forecasts. In the cloud, machine learning or statistical models can predict crop needs (for example, the development of development phase or disease risk). The cloud portal also allows farmers or agronomists to imagine the sensor trend, adjust the threshold and plan. By hosting Big-Data Analytics and Dashboard, Cloud Layer enables informed management decisions. Overall, the combination of IoT-sensing, fog processing and cloud computing forms a scalable accurate agricultural platform (Getahun et al., 2024).

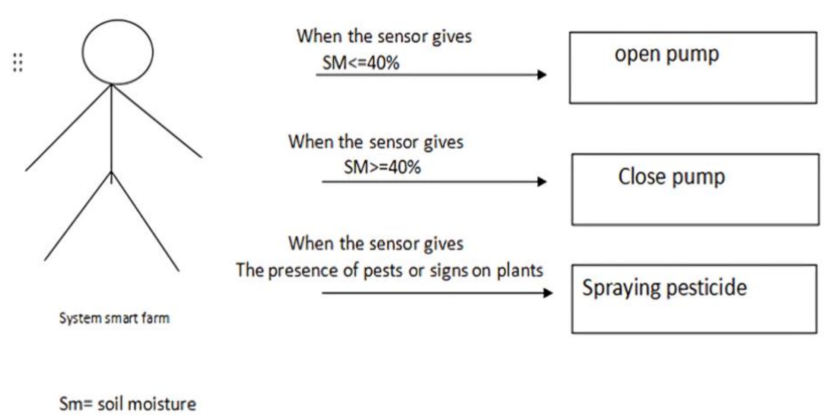

Fig. 1. Illustrates decision and control logic of the system

Figure 1 explains the core control logic of the system. When the soil moisture (SM) reports a volumetric water content of 40 percent or less, the fog opens the node. When the moisture increases above 40 percent, the pump is closed. Individually triggers insect or disease detection (such as image analysis) localized pesticides spraying. In fact, the system uses water or chemicals only when needed, with target intervention. This approach reflects the principles of accurate agriculture: sensors provide real-time data, enabling automatic, site-specific reactions (Mansoor et al., 2025). For example, similar systems use sensors thresholds to regulate pumps and protect them from crop voltage. A related variable fertilization function can be added, so that the reading of earth nutrients from the IoT layer that reaches and how much fertilizer to spread (matches the irrigation argument). In summary, the guidance argument only reduces waste by watering only low-Redundant and spraying only on the confirmed insect look, as shown in the simulation impact flow. Figure 2 shows the flowchart of the processes and the logical order of events in the IoT-enabled guidance-based system.

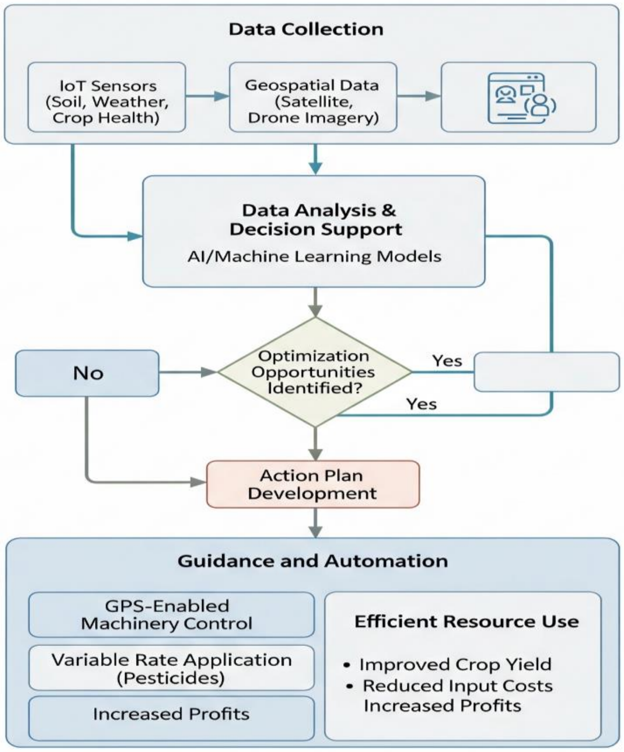

Figure 2. Illustrates the flowchart of the processes in IoT guidance-based system

3.2 Used Tool

iFogSim is a Java-based Open-Source simulation tool for simulating Fog and IoT enabled environments. It was developed by Harshit Gupta and the team at Cloud Computing and Distributed Systems (Clouds) Lab University of Melbourne Australia. iFogSim enables simulation of resource management and planning policies for applications. The simulator integrates different modules. The IoT device model is defined based on field level units and specific parameters, such as CPU use (Gupta et at., 2017).

The IoT application creates data processing elements based on specific application modules that are the objects that follow the tuples between sources and destinations. For a specific case of the selected landscape, each application matches a fog, that is, an increased installed to transfer data between sensors and clouds, or sensors and fog equipment.

3.3 Performance Evaluation Metrics

- ***Energy Efficiency:*** Energy input per unit of crop produced (e.g., mega joules per ton of crop) is known as energy use efficiency.
- ***Economic Metrics:***

  Cost of Production: The entire amount spent on labor, resources, and technology needed to produce one unit of a crop.
- ***Latency:***

  the delay brought on by data transmission across the network, including any delays brought on by routing issues, capacity restrictions, and network congestion.

4. Results

This section illustrates the results of applying the case study described in the previous section. Below is a review of the scenario topology after applying it to the iFogSim simulator, followed by the most important results in terms of energy consumption, latency and network bandwidth.

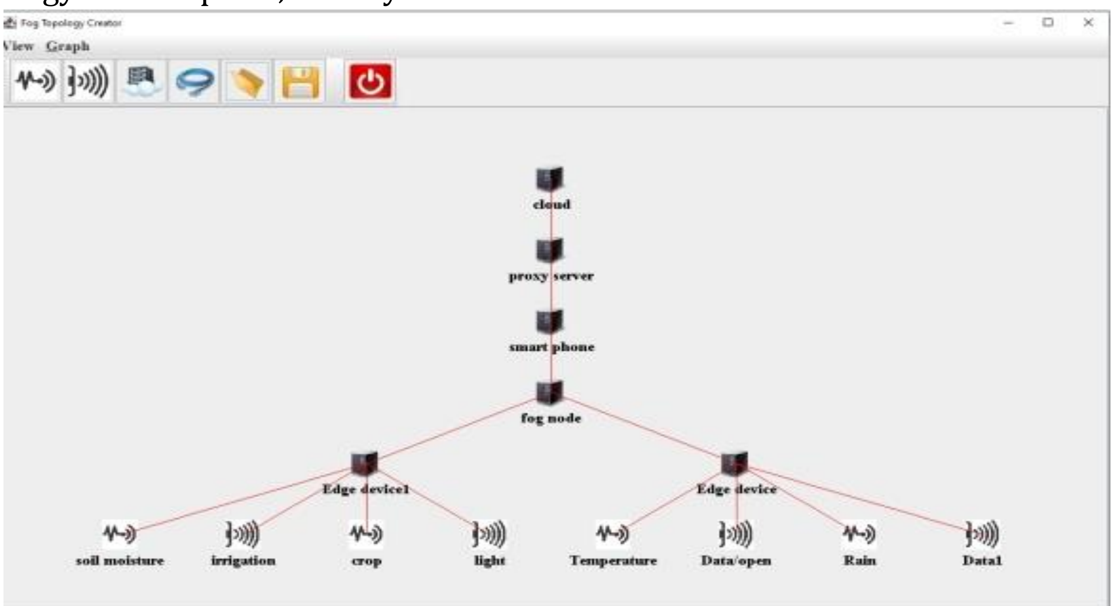

Fig. 2. Topology of Fog-based smart farming

The implemented fog-based smart framing (as shown in Fig. 2) consists of a distributed sensor–actuator network and hierarchical processing infrastructure intended to yield an ideal harvested crop through precision agriculture. In agricultural applications, soil moisture sensors continuously measure volumetric water content in soil, taking measurements at specified intervals, and actuate automatic irrigation actuators, such as sprinkler valves, when threshold values are met. Crop sensors measure crop health by measuring chlorophyll content, then actuates supplemental lighting when environmental conditions are conducive for optimal photosynthetic condition. Soil moisture sensors are not the only sensors measuring soil moisture. Soil sensors and ambient temperature sensors provide a measurement of the thermal condition of the soil, including air temperature, and provide control over heaters, fans, or ventilation when these temperatures exceed preset limits. Rain sensors measure atmospheric moisture when moisture creates a conductivity change by purposely allowing irrigation to be terminated to avoid water over application. Data collected by integrated IoT endpoints are subject to local processing on edge devices (e.g., field gateways) in order to eliminate latency and conserve bandwidth, whereupon data will be aggregated in fog nodes where additional processing enables real-time analytics (e.g., irrigation scheduling and pest alerts) with insights distilled and communicated to cloud servers. In the cloud layer, there is an opportunity for scalable storage, long- term historic analysis, and centralized decision support: while a proxy server secures the network traffic, and a smartphone application communicates real- time status, alerts to farmers and provisions for remote control.

Table 1 and 2 show the values that were used in the implementation of the topology in terms of devices and links (connections) among them.

Table 1. Topology devices configuration values

Devices	MIPS	RAM	Upstream	Downstream	level	RatePerMips
Cloud	100000	40000	10000	10000	0	0.01
Proxy Server	8000	4000	10000	10000	1	0.01
Fog node	4000	2000	5000	5000	3	0.01
Smart phone	1000	500	1000	1000	2	0.01
Edge device	3000	1000	10000	270	4	0.01

Table 2. Links latency default values

Source	Destination	Latency(ms)
Cloud	Proxy server	100
Proxy server	Smart phone	50
Smart phone	Fog node	30
Fog node	Edge device	20
Edge device	sensor	10
Edge device	Actuator	10

Figures 3 and 4 shows the simulation execution of the topology in terms of cost of execution and energy consumption and latency, respectively.

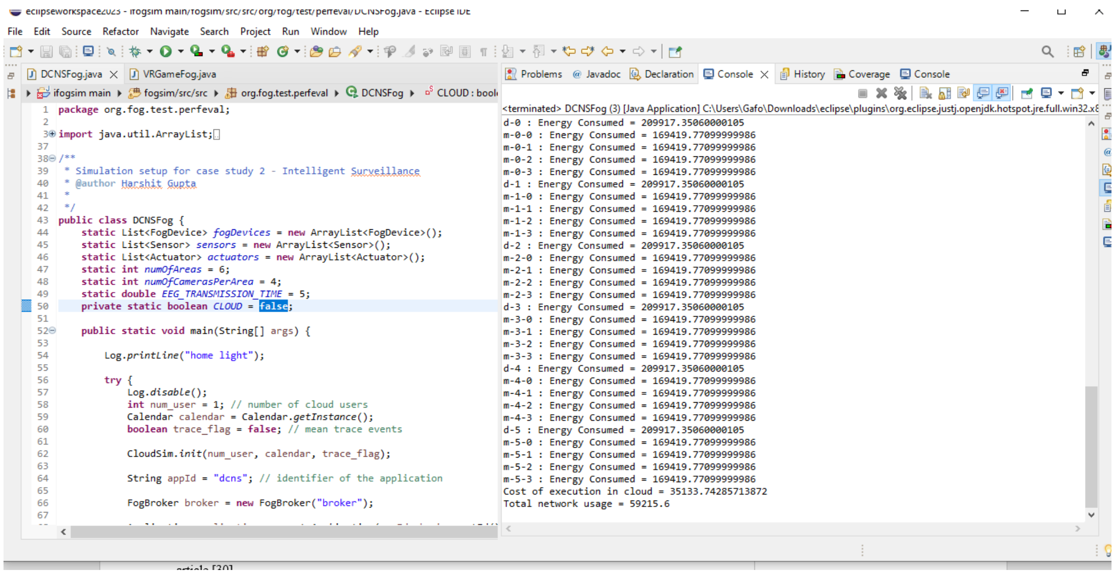

Fig. 3. Energy Consumption and cost of execution

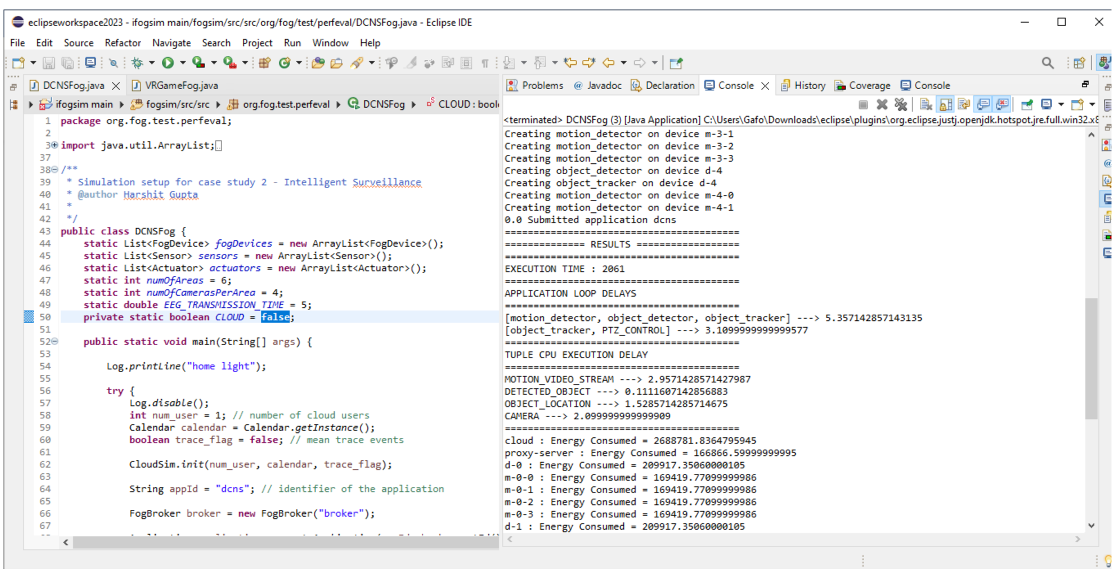

Fig. 4. Overall nodes latency

Table 3. Comparison of performance metrics in Fog and Cloud scenarios

Metric	Fog	Cloud-only
Latency (Delay)	6.67	32.81
Energy consumption	2668904.02	3240953.18
Network bandwidth	10871.6	11177.6

The following figure shows the efficiency of Fog enabled IoT-based guidance system compared to Cloud-only based system.

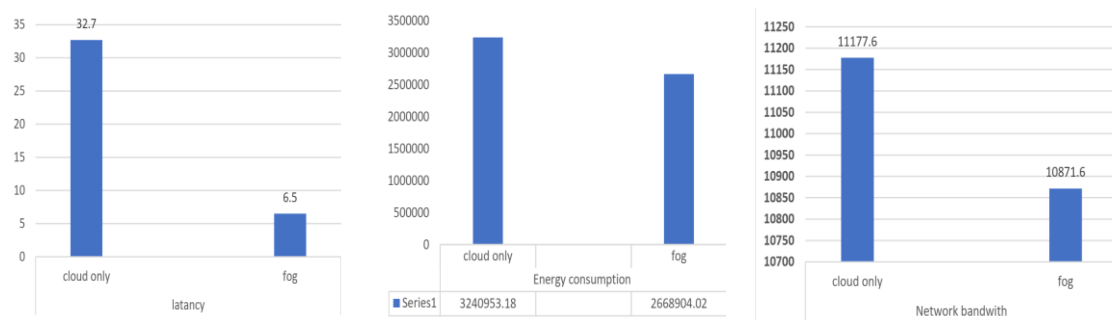

Fig. 5. Comparison between Fog enabled IoT-based guidance systems and Cloud-only ones in terms of latency, energy consumption and network bandwidth

5. Discussion

Punithavathi et al. (2023) examined the integration of data vision, deep learning and IoT) techniques to continue precision agriculture. In their structure, camera or drone images are analyzed through deep nerve networks to assess crop health, detect diseases and monitor soil conditions. Although this approach shows a strong capacity for automatic evaluation of pattern and development phase evaluation, it is forced by very accurate data collection and the need for intensive calculation resources. In addition, the first certification costs are sufficient, and centralized treatment of large versions of visual data shows delays that can delay important decision-making.

To address these limitations, our study expands topology by incorporating fog computing with IoT-based sensing. Environmental data is collected in the perimeter of the field and locally treated on fog nodes, which performs the real-time analysis near the data source. This edge/IoT layer proximal processing reduces end-to-end latency compared to architecture as well as energy consumption and the total execution cost, enabling more immediate responses to irrigation and insect/fertilizer treatment. As a result, resource efficiency is increased through adapted water and fertilizer distribution, and by reducing unnecessary data transfer and by enabling rapid corrective functions, operating costs are reduced.

Overall, the study is aimed at better crop monitoring and consequently farm management through the integration of IoT sensing, fog computing, and remote analytics. System simulations using our use case topology show that the platform met its design requirements and delivered real-time and accurate recommendations, while having acceptable performance across other metrics, such as response time, resource used, and decision accuracy. These results show the value of distributed processing in smart farms and further suggest an expandable framework for future precision agriculture systems.

Conclusion

The integration of IoT and fog computing in precision agriculture is driving a revolutionary change in traditional farming that allows for real- time monitoring, data collection, and analysis in ways that measurably increase efficiency, productivity, and sustainability. IoT device deployment can generate large data sets from sensors for soil moisture, temperature, and crop- health that allow farmers actionable insight to optimize their resources, minimize waste, and increase yields. Fog computing moves cloud capabilities down to the edge of the network in order to mitigate the impacts of cloud latency and bandwidth limitations to ensure time-critical data processing and reliable automated responses during agricultural operations. Simulation experiment results reported in iFogSim show that this IoT-fog cadre has significant advantages over traditional cloud-only approaches in all three-performance metrics, solidifying its place in meeting the needs of the growing global food supply deficit and food security amidst current and future climate change scenarios. Our future work will focus on a real field experiment on sugar or wheat crops and comparing the simulation results with actual results.

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