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Development of IoT Cloud-based Platform for Smart Farming in the Sub-saharan Africa with Implementation of Smart-irrigation as Test-Case

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Abstract: UN Department of Economics and Social Affairs predicted that the world population will increase by 2 billion in 2050 with over 50% from the Sub-Saharan Africa (SSA). Considering the level of poverty and food insecurity in the region, there is an urgent need for a sustainable increase in agricultural produce. However, farming approach in the region is primarily traditional. Traditional farming is characterized by high labor costs, low production, and under/oversupply of farm inputs. All these factors make farming unappealing to many. The use of digital technologies such as broadband, Internet of Things (IoT), Cloud computing, and Big Data Analytics promise improved returns on agricultural investments and could make farming appealing even to the youth. However, initial cost of smart farming could be high. Therefore, development of a dedicated IoT cloud-based platform is imperative. Then farmers could subscribe and have their farms managed on the platform. It should be noted that majority of farmers in SSA are smallholders who are poor, uneducated, and live in rural areas but produce about 80% of the food. They majorly use 2G phones, which are not internet enabled. These peculiarities must be factored into the design of any functional IoT platform that would serve this group. This paper presents the development of such a platform, which was tested with smart irrigation of maize crops in a testbed. Besides the convenience provided by the smart system, it recorded irrigation water saving of over 36% compared to the control method which demonstrates how irrigation is done traditionally.

Index Terms: Smart Farming, IoT, Cloud-based Platform, Smart Irrigation, Sub-Saharan Africa.

1. Introduction

The Sub-Saharan Africa (SSA) is one of the world's poorest regions [1–5], by 2030, nearly 9 out of every 10 persons living in the region will be in abject poverty [6] (see Fig.1). This poverty is made most evident by the level of food insecurity in the SSA. Global and regional debates on lifting SSA out of poverty mostly reference agriculture because it is the sector where the poor can easily find a livelihood. Agriculture has the potential to provide food sufficiency and eradicate poverty in the region only if they can produce their food by themselves [7].

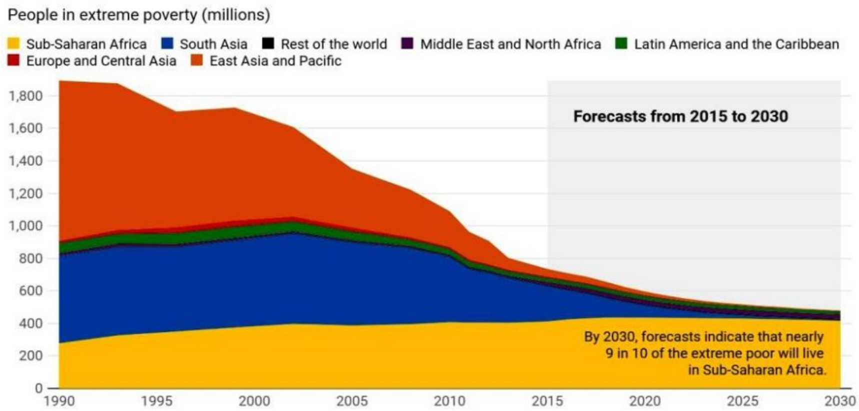

Fig.1. Distribution of poor people across global regions.

The UN Department of Economic and Social Affairs [8] predicted that the world population will increase by 2 billion in 2050 with over 50% from SSA. Thus, the urgent need to attack food insecurity in the region. According to the UN's Food and Agriculture Organization (FAO) [9], the agricultural market in SSA will grow from $200 billion (US) in 2015 to $1 trillion (US) by 2030.

This offers both a challenge and an opportunity for small-scale farmers and investors in the region. More persons are now venturing into agriculture as a means of livelihood. In Nigeria for example, about 65% of the workforce have keyed into the sector, contributing to 37% of her GDP[10]. In the same vein, about 75% of people living in abject poverty in the region, live in rural areas and depend largely on agriculture for survival [11].

However, farming approach in the region is primarily traditional. Traditional farming is characterized by high labor costs, low production, and insufficient or excessive supply of farm inputs [12,13]. All of these factors make farming unappealing to many. The use of digital technologies such as broadband Internet of Things (IoT), Cloud Computing, and Big Data Analytics promise improved returns on agricultural investments. It also simplifies farming, minimizes waste, and lowers labor costs, making farming appealing, particularly to young people.

However, the initial cost of smart farming could be high. Therefore, development of a dedicated IoT cloud-based platform is imperative. Such platform provides a data warehouse where data from sensors are stored and processed for monitoring, control, predictive analytics, etc. It could also accommodate millions of farmers and provide global view of happenings in the agricultural sector.

It should be noted that the vast majority of farmers in SSA are smallholder farmers who are poor, uneducated, and live in rural areas despite producing approximately 80% of the food [5,12]. Many of them do not have internet-enabled phones; instead, they primarily use 2G phones. These characteristics must be considered when designing any functional IoT platform that will serve this group.

Given the importance of agriculture in lifting SSA out of poverty and providing food sufficiency, a dedicated IoT cloud-based platform tailored to farmers in the region is required. This paper describes the creation of such a platform, detailing its design, implementation, testing and performance analysis phases the remaining part of this paper is organized as follows: Section 2 explores related works, section 3 discusses the methodology employed in this work, section 4 presents and discusses the results obtained while section 5 concludes the paper.

2. Related Works

The emergence and popularity of IoT is encouraging researchers, vendors, and businesses to develop new use cases and application areas. As a result, cloud-based platforms that support IoT use cases are also emerging. The design focus of these platforms varies, resulting in platforms that provide better services than others. Authors in literature have conducted interesting reviews on some of the IoT cloud platforms, focusing their discussion on various aspects of these platforms in order to expose readers to the offerings of the reviewed platforms while also identifying interesting gaps.

Pierleoni et al. [14] compared Amazon Web, Google Cloud, and Microsoft Azure IoT services. They mapped IoT-cloud services to the conventional IoT reference architecture and broke down platform costs by load to let developers choose a platform based on use case. This work [14] tried to compare existing platforms based on their offerings. The core features possessed by the mainstream platforms were captured in the design of the dedicated platform developed in this study. Similarly, Mahbub [15] described farm management systems using Embedded systems, IoT, and Wireless Sensor Networks. He described systems' electronic circuits, network protocols, and monitoring equipment. He showed that smart farming reduces costs and waste, allowing for better agricultural production control. The author suggested incorporating AI and ML into IoT-based smart agriculture. Thus, in this work, fuzzy logic-based algorithm was used to drive the irrigation algorithm that handle irrigation scheduling.

Sarhan [16] suggested the Galliot platform to accelerate and simplify IoT project development. The platform collects, processes, stores, manages, and integrates data with external systems. It uses a NoSQL database for schema flexibility and scalability. It manages users, projects, and devices but not reports and future events. This platform lacks the module for compiling reports based on farmers' needs and no AI algorithm was implemented for predictive analysis. Nothing that these omissions are core requirements of a dedicated IoT platform, they were integrated at the business logic layer in the design process of the developed platform.

Köksal & Tekinerdogan [17] presented a step-by-step modeling technique for IoT cloud-based Farm Management Information System (FMIS) architecture. The approach was evaluated in two smart farming case studies in turkey. The authors used IoT and FMIS reference models to create a customized IoT-based FMIS architecture. Case studies demonstrated that the approach was effective, however the implementation of their architecture was not captured. Furthermore, Bangare et al. [18] proposed cloud-based drip irrigation. The Arduino Uno microcontroller, sensors, actuator, and cloud server provided real-time monitoring and control over Wi-Fi. However, it was unclear how the IoT and cloud interface was handled. However, this work shows a well detailed layered design of a dedicated IoT platform, as well as its implementation and testing processes.

Kamienski et al. [19] introduced an IoT-based smart irrigation platform. They verified its replicability and scalability by measuring the performance of the FIWARE components deployed. The platform was tested in Brazil, Spain, and Italy. Their results showed great platform performance that can be optimized by reconfiguring FIWARE components. This platform achieves the core requirements of an IoT platform, but it is a general-purpose splatform and lacks the potential to meet the unique needs of a special group. This paper presents the developmental processes of a dedicated IoT platform that address the needs of farmers in the SSA region.

According to literature, no IoT cloud platform exist for a specific industrial sector, such as agriculture. Existing platforms are omnibus, serving many applications. Literature [20] also uncovered that existing IoT cloud platforms are expensive for farming in SSA and are not accessible with 2G phones typically used by farmers in the region. These difficulties will deter local farmers from using the technology. This research aims to close this gap by developing a 2G-accessible IoT cloud-based platform dedicated for smart farming, and test it with a smart irrigation.

3. Methodology

This section discusses the techniques and tools by which the objectives of this study are achieved. The design, development, and testing phases which constitute the core objectives are discussed in detail.

3.1. Design Phase

In this phase, an eight-layered architecture (see Fig.2) is designed for a dedicated platform for smart farming in the SSA by capturing the various modules that generate, transmit, process, and store data, and modules that enable farmers to use the processed data to carry out useful remote applications on their farms and manage associated devices and users. It is a framework for implementing IoT cloud solutions for industry 4.0 applications.

The architecture shows how each layer handles data; how data traverse from one layer to another; how security is spread across each layer; and needful mechanisms for data security. Unlike the architectures presented by [21] and [22], this architecture is dedicated to IoT for agriculture. It is simple to implement, cost-efficient, scalable and addresses security concerns in a bottom-top approach. The various layers of the architecture are hence discussed in detail.

Data Source Layer

The edge network layer or data source connects the farm to the cloud. The sensor nodes, actuator nodes, and gateway make up this layer. At the edge of the Wireless Sensor Network (WSN) and the cloud is the gateway. Through communication protocols such as Z-wave, Bluetooth, ZigBee, WiFi, LoRa, etc., the sensor and actuator nodes can communicate with the gateway [23]. Fig.3 depicts the data source layer model.

Data Injection Layer

This is the point at which data enters the cloud. It includes the communication protocols used to establish handshake between the gateway and the cloud such as Message Queuing Telemetry Transport (MQTT), Advance Message Queuing Protocol (AMQP), Extensible Messaging and Presence Protocol (XMPP), Constrained Application Protocol (CoAP), HyperText Transfer Protocol (HTTP), etc. (see Fig.4). Data exchange between the edge and the cloud network is formatted in either plain text, Comma Separated Values (CSV), Extensible Markup Language (XML) or JavaScript Object Notation (JSON).

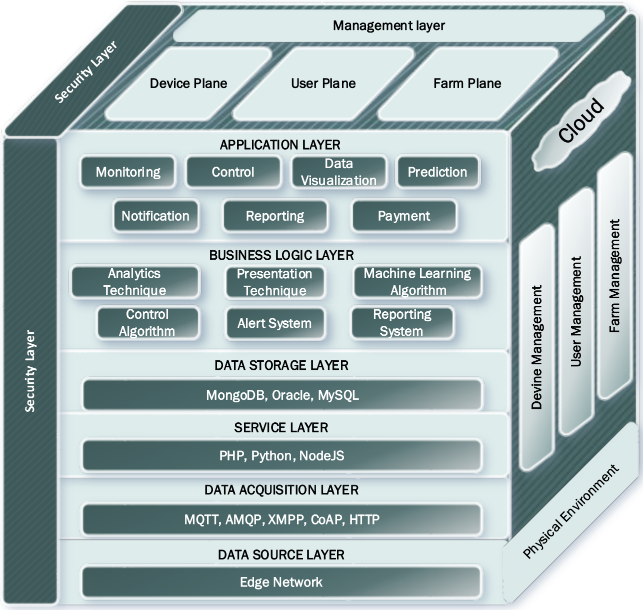

Fig.2. 8-Layer Model Architecture for Smart Farming.

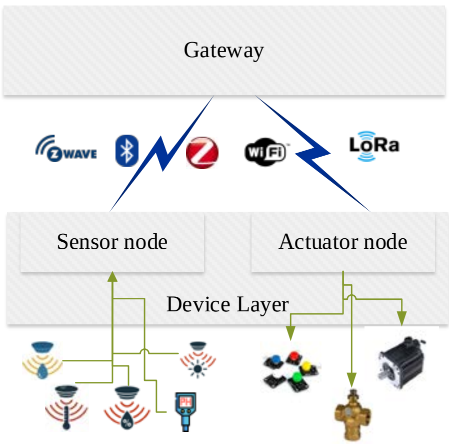

Fig.3. Data Source Layer Model.

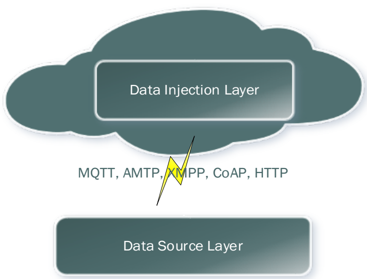

Fig.4. Data Injection Layer Model.

Data Storage Layer

This is the layer where all collected data are stored. It is the backbone of the cloud platform. It is strongly advised that the database server deployed in this layer be both horizontally and vertically scalable to accommodate farms of varying sizes. Database servers include MySQL, SQL Server, PostgreSQL, MongoDB, and Oracle, among others [24]. The design model of the communication between the database and the edge network is shown in Fig.5

Business Logic Layer

The business logic layer is the layer where computer languages are used to manipulate data in order to create applications. In this layer, techniques for data visualization applications, control algorithms, machine learning algorithms for predictive analysis [25–28], etc., are configured.

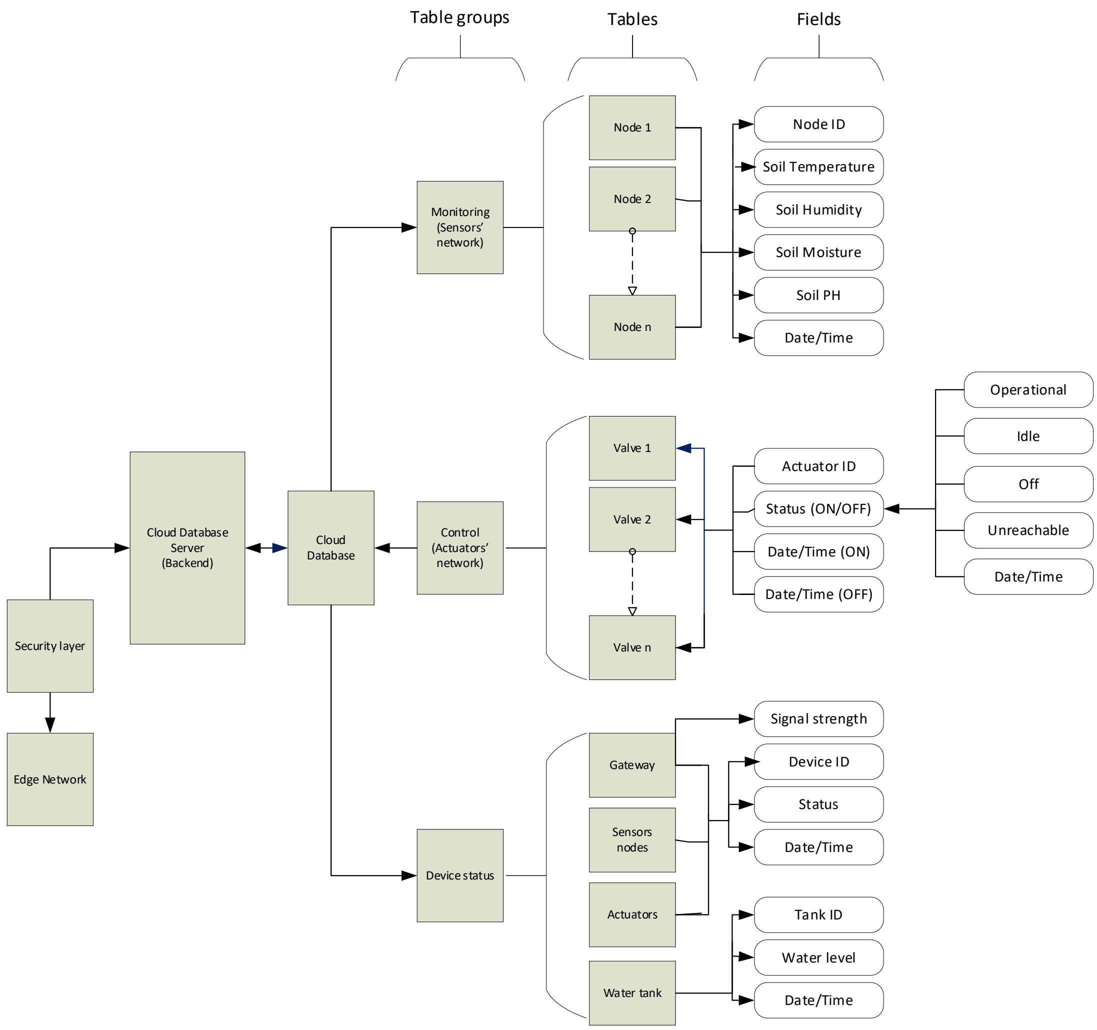

Fig.5. Communication Model between the Cloud Database and the Edge Network.

Application Layer

This is the layer that is responsible for providing the interface via which farmers may interact with their farms, monitor and control events, receive notifications, generate reports, and so on. It is essential that the application layer be easy to use, particularly for farmers in the SSA.

Management Layer

This is the layer that is responsible for the virtual management of farms, devices, and users. Some of the functions of management include the addition and deletion of nodes and users, the creation and deletion of farms, the division of farm into plots, and other similar tasks.

Security Layer

In this design, this layer spans all other layers to secure the confidentiality, integrity, and availability of users and data. At the data source layer, the security considerations are how to transport data securely and guarantee that only designated nodes send and receive data. Before data exchange can occur, nodes must be individually identified and authenticated to overcome this risk. For data confidentiality, Harsing algorithms can be employed to encrypt transmitted data. All data exchange points between layers 2 and 6 (cloud network) should be protected by Transport Layer Security/Secure Socket Layer (TLS/SSL). Every data request from a user or process must be subject to authentication, and all data on transit must be encrypted. All devices and users must be properly registered and validated at the administrative layer. User rights and permissions must be precisely defined, and all user actions must be trackable to ensure non-repudiation.

3.2. Development Phase

This section outlines the process by which the designed architecture is transformed into an IoT cloud platform. Each layer's design and justifications for selection of technologies and protocols are described.

Layer 1

At the data source layer, LoRa is used for sensor and actuator node communication with the gateway. LoRa is chosen over Z-wave, ZigBee, Bluetooth, and WiFi due to its longer range (approximately 15 km in open space, suitable for farms) and reasonable power consumption [28].

Layer 2

At the data injection layer, the MQTT protocol is employed for cloud communication. It is chosen over AMQP, XMPP, CoAP, and HTTP because it is energy-efficient, lightweight, and has a higher tolerance for poor network connectivity.

Layer 3

Python is used at the service layer to route received data in the cloud to the database. Python is used over PHP, NodeJS, and other frameworks due to its high level of flexibility with the MQTT protocol. Paho Python MQTT Client is its MQTT library. It includes a client class that supports MQTT versions 2.7 through 5.0 [29].

Layer 4

MySQL is favored at the database layer over other database management systems such as MongoDB, Oracle, PostgreSQL, MariaDB, etc. due to the fact that it is simple to deploy, has a larger community of developers, and can be scaled both vertically and horizontally. In addition to this, it is compatible with programs written in Structured Query Language (SQL) as well as Not only SQL (NoSQL).

Layer 5

At the business logic layer, Python and PHP are used to set up the logic for the applications that are needed in layer 6. The control algorithm and the machine learning algorithm for predictive analysis were both written in Python. PHP, on the other hand, is used to implement the techniques for presenting data. It was also used to set up the system for alerts and reports.

Layer 6

JavaScript and CSS were used to design the user interface on the application layer. Farmers may easily perform the numerous actions specified in the business logic layer thanks to the user interface's simplicity.

Layer 7

The farm, nodes, and users are configured and controlled at the management layer. This layer implements many management subsystems, including user registration, authentication, device management, and farm management.

Layer 8

At the security layer, nodes are assigned unique identifiers that have been registered in the cloud. TLS and SSL are used to communicate securely across implicit and explicit connections, respectively. Users and devices are authenticated prior to data access.

3.3. External SMS Query Module

The SMS query service module is an external component of the cloud platform that enables devices without Internet connectivity to interface with the platform via SMS query service. The cloud component of the module is implemented on the cloud platform's business logic layer (layer 5). The module is created using the JAVA programming language. It is installed on an Android smartphone, which acts as an arbitration server between 2G phones and the cloud. The aforementioned module has a method that automatically examines SMS for the presence of a query parameter. If a query parameter exists, the query service retrieves it along with the sender's phone number and sends it to the cloud platform using an SMS read-forward method. A query parameter is a keyword that is recognizable by the SMS query module and the cloud platform. It is used to processes requests from 2G devices. The module's SMS read-forward method is created with the Android telephone Manager class.

At layer 5 of the cloud platform, the sent data is received via an Application Program Interface (API) built with a PHP-MySQL read query string. The cloud server verifies whether the sender's phone number is registered with a farm. If so, it employs the query parameter to process the request and sends the response back to the arbitration server for onward delivery to the 2G device. Otherwise, the argument is marked as "unknown source" and discarded. If the cloud offers an SMS service, the response could simply be transmitted to the 2G device directly. In this work, the cloud platform returns the response to the arbitration server, which then transmits the response to the 2G device (see Fig.6). The SMS query module of the arbitration server operates in the foreground to check for incoming messages containing a query parameter. This module attribute was created using the SMS broadcast class.

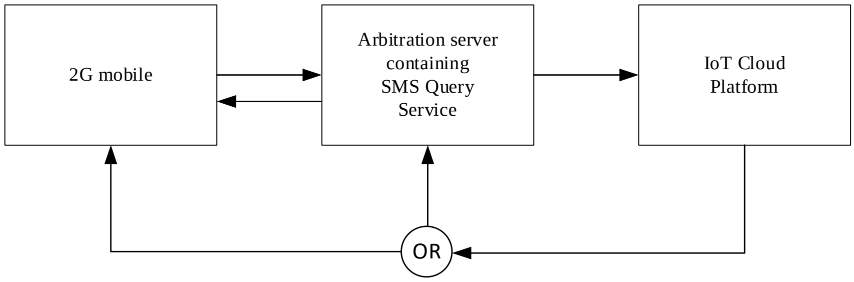

Fig.6. SMS Query Module.

The query parameters are presented in Table 1, and the SMS module flowchart is shown in Fig.7.

Table 1. SMS Query Parameter.

SN	Query parameter	Action
1	wl	Returns the water volume of all tanks registered on the user’s farm
2	li	Returns the date and time of last irrigation and the volume of water dispensed
3	mir	Returns monthly irrigation report
4	aft	Returns the average day-time and night-time farm temperature of the last 24 hours
5	afh	Returns the average day-time and night-time farm humidity

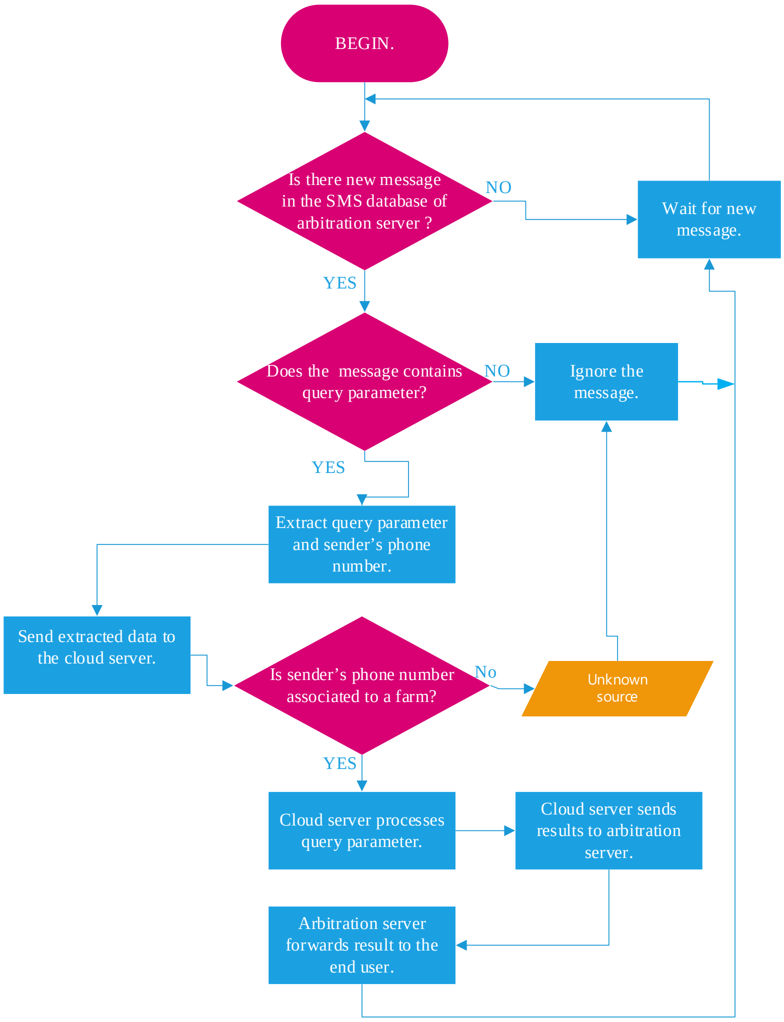

Fig.7. Flowchart of SMS Query Module Algorithm.

3.4. Testing Phase

A fuzzy logic-based irrigation scheduling algorithm was installed on the developed smart farming platform and tested on a maize farm testbed set up in Federal University of Technology (FUT) Minna shown in Fig.8.

Fig.8. FUT Minna ongoing smart irrigation testbed a) farm office, b) maize farm, c) solar powered sensor node, d) water tanks, e) shed for solar powered sensors (water flow and water level sensors) & actuator nodes.

The smart irrigation testbed consists of two (2) farms – A & B; with 12 plots each. A is the smart irrigation farm while B is the control (non-smart). Farm B typifies traditional irrigation technique where water is supply at fixed intervals daily. Its essence is to provide a level ground to measure and validate the efficacy of the smart system in terms of resource conservation. Plots of A are alternated with plots of B in a staggered fashion, as shown in the farm schematic of Fig.9, to avoid bias in the treatments.

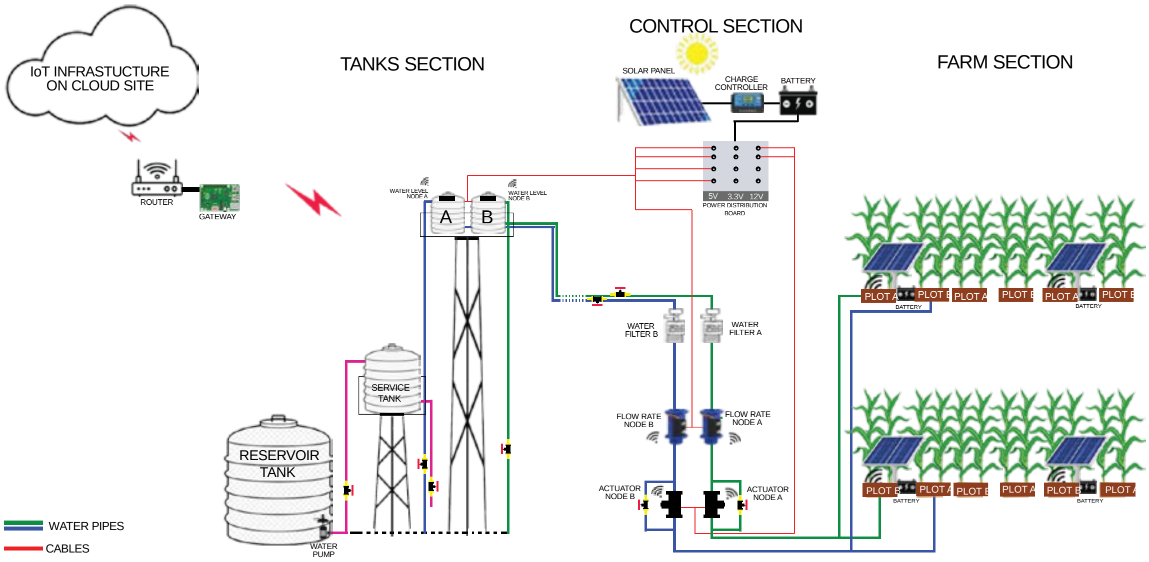

Fig.9. Schematic of smart irrigation testbed.

The smart irrigation scheduling algorithm was used to irrigate farm A automatically based on real-time sensor data received from the farm [30]. Farm B on the other hand was irrigated using a simple non-smart algorithm that activates the actuator at predetermined times daily, in accordance with traditional practice. Farm A consists of a total of 7 nodes and 18 sensors, comprising 1 actuator node, 1 water level sensor node, 1 flowrate sensor node, and 4 other nodes each containing 2 moisture sensors, 1 temperature sensor, and 1 humidity sensor. Plot B has a total of 3 nodes and 2 sensors, comprising 1 actuator node, a water level node, and a flow rate sensor node.

4. Result and Discussion

This section discusses the outcomes of the developed platform, analyzes the volume of water dispensed in the smart and control farms, and gives an analysis of the platform's performance.

4.1. Platform Development Results

Fig.10 showcases a section of the platform's dashboard. The dashboard displays the status of the gateway and nodes, data received, and irrigation events.

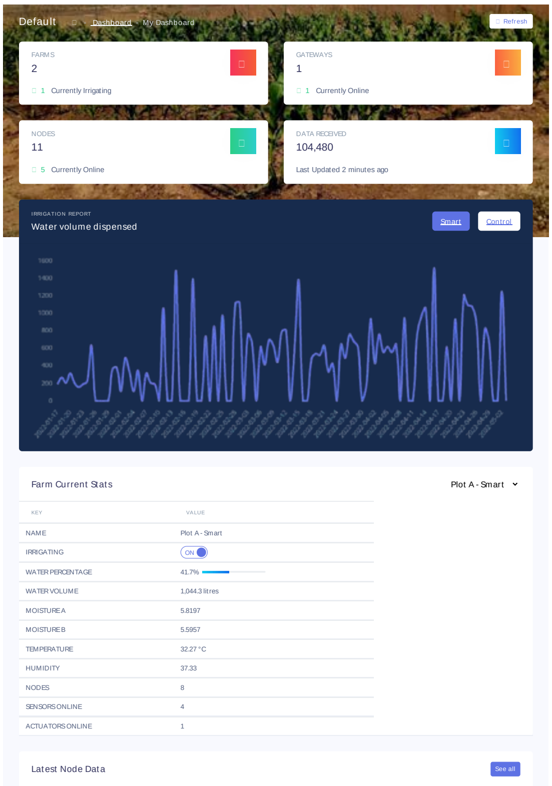

Fig.10. Cloud platform dashboard.

The dashboard comprises a status indicator that displays the state of each farm and a sidebar with connections to the platform's many modules. The farm module includes registration functions for farms on the platform. It records information such as the type of soil on the farms and the crop to be grown. The device module consists of operations for adding, removing, and controlling gateway, sensor, and actuator nodes. Eleven (11) nodes from both farms are connected to the cloud, as shown in Fig.10, but only five (5) are online. A node is considered to be online when it is communicating with the cloud server. An offline status indicates that the node is idle or faulty. When a node is offline longer than its data idle state period, there is a chance of an electronic issue or persistently poor network connectivity.

The user/staff module consists of tools for adding and removing users from a farm's cloud platform. The farm manager has complete access and selects other users' access levels. The settings section includes features for controlling the cloud service, modifying crop and soil characteristics, and establishing an irrigation plan. Under the module's settings panel, the cloud service that integrates the farm with the cloud is managed. The log module provides a record of the irrigation algorithm's actions, while the schedule module has a calendar where events are labeled with dates. Fig.11 shows the growth stages of the maize crop in the experimental farm from week 1 to week 6

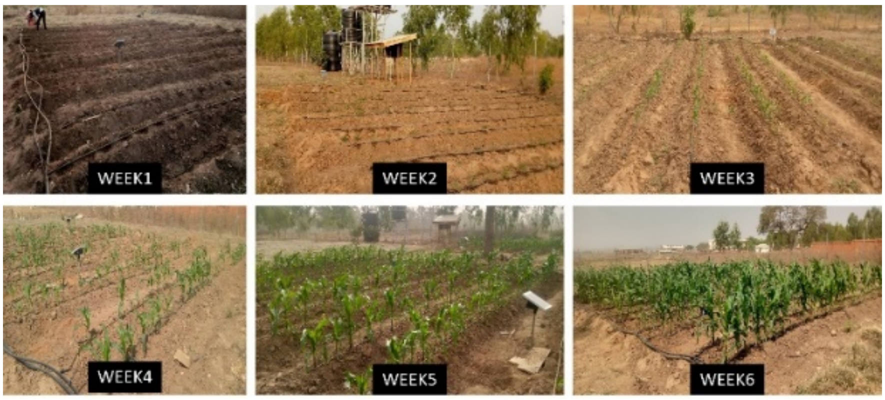

Fig.11. Growth stages of maize crop in the experimental farm.

4.2. Analysis of Water Volume Dispensed

The volume of water dispensed in the smart farm by the smart irrigation algorithm installed on the cloud-platform is given on the graph displayed on the dashboard in Fig.10 while that of the control farm is presented in Fig.12.

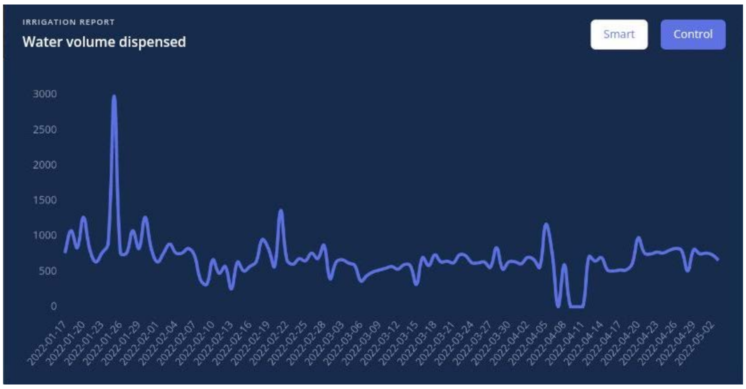

Fig.12. Water volume dispensed in the control farm.

As reported by the cloud platform, a total water volume of 46,392 litres and 73,251 litres was dispensed on the smart farm and control respectively, from the date of planting (January 17, 2022) to harvest (May 2, 2022); a total of 15 weeks. This shows that the smart algorithm saved water by 36.67% according to (1)

$$V_{\%} = \frac{V_C - V_S}{V_C} \tag{1}$$

$V_{\%}$ is the percentage of water saved by the smart irrigation system while V_C and V_S are the water volumes consumed by the control and smart farm respectively.

4.3. Performance Analysis

Site24*7, a web monitoring and diagnostic tool (Website Monitoring Service, Server Monitoring: Site24x7), was used to measure the response time over a 5-month period (November 1 to March 32, 2022). Site24x7 offers a complete cloud monitoring solution for development and IT operations to both small and large businesses. The service tracks desktop and mobile user interactions with websites and applications in the real world. It provides monitoring capabilities that enable development teams to monitor and debug the entire architecture of an application, including servers, networks, and public clouds. Monitoring of the end-user experience is undertaken from over 100 sites worldwide and across numerous cellular providers [31].

The performance of the developed platform was analyzed in terms of response time and system stability, using descriptive and statistical models such as mean and coefficient of variation respectively [32].

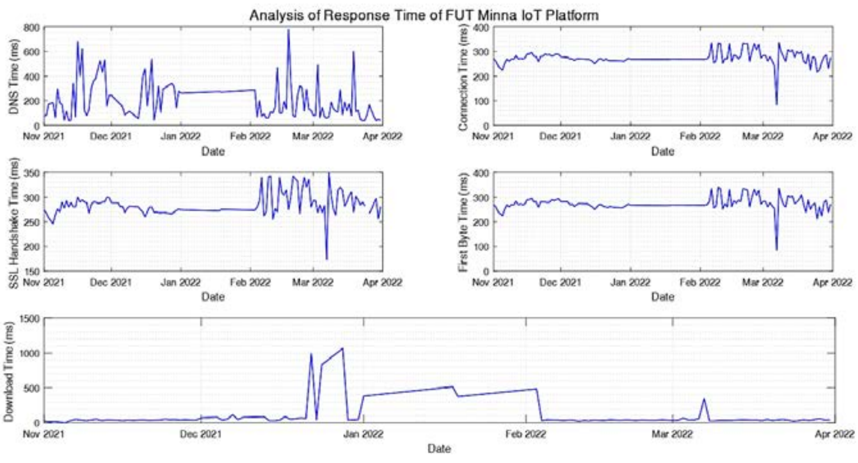

Fig.13. Analysis of Response Time.

Response Time

The time it takes a system to respond to a service request is known as response time. The Domain Name Service (DNS) resolution time, connection time, Secured Socket Layer (SSL) handshake time, first byte load time, and download time are all factors in IoT cloud platforms. Fig.13 depicts a descriptive analysis of the developed platform's response time.

Fig.13 shows that the average DNS time, connection time, SSL handshake time, first byte time, and download time are 234 milliseconds, 270 milliseconds, 278, 270 milliseconds, and 48 milliseconds, respectively. The average overall response time is 1 second. According to Nielsen's research, this is sufficient for a satisfactory user experience [33].

System Stability

A system's stability, in addition to its response speed, has a substantial impact on the quality of user experience. The user experience is significantly impacted if there is a large disparity in system response. The response time characteristics of the developed platform reveal that DNS resolution time has a significant impact on system stability. A computational examination of the platforms' variableness was necessary to justify this.

The coefficients of variation (CV) of the various components of the response time were computed using (2). Table 2 shows the calculated coefficient of variation, as well as the standard deviation (σ), mean ($\overline{x}$) and system's stability ($Stability$) computed using (3), (4) and (5) respectively.

$$CV = \frac{\sigma}{\overline{x}} \tag{2}$$

$$\overline{x} = \frac{\sum_{i=1}^{N} x_i}{N} \tag{3}$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N} | x - \overline{x} |^2}{N}} \tag{4}$$

$$Stability = 100 \times (1 - CV) \tag{5}$$

Table 2. Analysis of System Stability.

SN	Response Time	σ (ms)	$\overline{x}$ (ms)	CV	*Stability*	*Stability*(%)
1	DNS Resolution time	156	233.9	0.67	0.33	33.14
2	Connection time	13	269.6	0.05	0.95	95.10
3	SSL Handshake time	12	278.4	0.04	0.96	95.85
4	First byte time	14	269.5	0.05	0.95	94.91
5	Download time	21	48.3	0.43	0.57	56.94
6	Overall Response Time	170	1099	0.15	0.85	84.54

As illustrated in Fig.13, Table 2 demonstrates that the DNS resolution operation has a significant impact on the system stability. This is a function of the platform's underlying hardware infrastructure. However, the total system stability is adequate at 84.54%, allowing for a satisfactory user experience.

5. Conclusions

This paper reported the development of a flexible IoT Cloud-based platform dedicated for smart farming in the Sub-Saharan African region. It was noted that it was imperative to develop such platform in order to guarantee sufficient and sustainable food production for the teeming population in the region. According to literature, Sub-Saharan African farmers are predominantly uneducated smallholder farmers living in rural areas with limited internet access, although they produce approximately 80% of the food [5,12]. Therefore, the IoT cloud-based platform presented here was developed to accommodate the peculiar needs of these important group of farmers. Given that farming is a lever with which SSA could be lifted from poverty into food sufficiency, the developed platform is dedicated to smart farming in order to give a wide range of agricultural support to farmers thereby making rural farmers digitally inclusive. According to literature, existing platforms cannot be used with non-internet-enabled devices typically used by farmers in the region. This work has also filled this gap by building an SMS query service that allows farmers to connect to the platform using 2G phones that is common among them. The platform was tested by implementing a smart irrigation of maize crops on a testbed. Besides the convenience provided by the system and savings in labour cost, it recorded savings in irrigation water of over 36% compared to the control system which represents traditional irrigation technique. The system performance was also analyzed in terms of response time, and system stability from data gathered over a period of 5 months. According to the results, it has an average response time of about 1s and a system stability of 84.54%, which in comparison to Nielsen's study on usability engineering, are suitable for a befitting user experience [33].

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