Hindawi
International Journal of Distributed Sensor Networks
Volume 2023, Article ID 4803000, 11 pages
https://doi.org/10.1155/2023/4803000

SAGE Publishing

Research Article

IoT-Based Real-Time Crop Drying and Storage Monitoring System

Ishimwe Viviane,[1,2] **Emmanuel Masabo**,[1,3] **Habiyaremye Joseph**,[1] **Mitsindo Rene**,[1] **and Elias Bizuru**[1,4]

[1]*African Centre of Excellence in the Internet of Things, University of Rwanda, KN 7 Ave, Kigali, Rwanda*
[2]*Integrated Polytechnic Regional College Musanze, Rwanda Polytechnic, KK 15, Kigali, Rwanda*
[3]*African Centre of Excellence in Data Science, University of Rwanda, KN 7 Ave, Kigali, Rwanda*
[4]*Centre of Excellence in Biodiversity and Natural Resource Management, University of Rwanda, KN 7 Ave, Kigali, Rwanda*

Correspondence should be addressed to Ishimwe Viviane; vivianeishimwe36@gmail.com

Received 20 November 2022; Revised 3 August 2023; Accepted 25 August 2023; Published 26 September 2023

Academic Editor: Michele Amoretti

Maize flour obtained from the dried corn is one of the most consumed foods in Rwanda. It is imperative that this should be healthy and risk-free for a safe consumption. Therefore, it is vital to keep track of the environmental conditions during the drying process and the characteristics that exist inside maize storage containers. In Rwanda, traditional methods are most commonly used by maize farmers for drying and storage purposes, where no smart system is being used to monitor the environmental conditions under which the maize grains are dried and stored. This mostly affects the quality of maize and flour being produced which will finally affect food security. In this research, temperature, humidity, and light sensors are deployed in the grain storage containers for environmental parameter detection purposes to achieve the primary goal of providing practical, secure, and easily accessible storage in inclement weather. Temperature and humidity are two factors that have an impact on grain quality while in storage. The ThingSpeak platform has been used to help farmers monitor the drying and storing conditions of the maize on a real-time basis. A global system for mobile (GSM) communication module is used to notify farmers by sending a short message in case of critical drying or storing environmental parameters under which the maize grains are stored. The result is shown in the form of humidity, temperature, and light graphs which are displayed on the ThingSpeak platform in real-time mode.

1. Introduction

Rwanda produces around 700,000 tons of maize every year [1], and the active breeders report a satisfaction rating of 77% in maize [2]. However, a substantial portion of it is rejected by agroprocessing companies due to aflatoxin-related poor quality. The sixth priority area of the National Strategy for Transformation (NST1) of Rwanda is targeting to modernize and increase the productivity of agriculture and livestock, in which building postharvest handling and storage facilities across the country and adding value to agricultural production has been identified as a key strategic intervention. In the Industrial Master Plan for the Agro-Processing Subsector (2014-2020) developed by the Ministry of Trade and Industry (MINICOM), an agroprocessing subsector master plan has been developed [3] to enhance technology in postharvest handling.

The transport of maize corns from the field to the drying space is performed using casual labor. Many organizations have a well-managed drying area and a hangar. During drying, maize corns are sorted and those which are inadequate for seed are removed. Selected ones are dried up at 12% grain moisture content; they are shelled and finally threshed to remove foreign bodies and malformed grain. Shelling and threshing are performed by hand [4]. According to a 2013 Ministry of Agriculture and Animal Resources in Rwanda (MINAGRI) assessment on maize production, there is a significant rate of postharvest loss (22 percent) due to poor handling, drying, and storage of crop harvest, and it is recommended that existing measures to develop maize cooperatives have to be strengthened to reduce postharvest losses, enhance yields, and improve crop quality [5, 6].

Due to operational weaknesses and constraints at some stages in the chain, such as maize production on farms (lack of inputs, credit access, and price fluctuation) and processing at plants (irregular and insufficient supply), and low quality of drying and storage processes, local maize production is unable to meet the strong demand in the growing trend of maize-based products [7]. Assessment has been conducted on the postharvest quality and economic loss [8] Due to suboptimal farming methods, smallholder maize growers are experiencing huge yield discrepancies [9].

The Internet of Things (IoT) plays an impactful role in solving these issues, by monitoring in a real-time basis the maize drying process at every stage and notifying farmers in case of critical conditions, to act accordingly. Some sensors are to be incorporated in the system for sending data over the Internet. It enables farmers to monitor their maize remotely from any place by using a cellphone or a computer and even on-site monitoring through a liquid crystal display (LCD). This IoT system is very useful to farmers because when critical storage conditions are detected, the farmer can modify the storage environment or even relocate maize to new storage.

Traditional methods are mostly used by farmers to dry and store their crops; yet vision 2050 in Rwanda focuses on stressing the importance of agroprocessing: advanced food industry and technology-intensive agriculture with a commercial focus under pillar II [10]. Farmers have to be physically present at drying sites to handle drying issues which usually takes about 3 months which is a long time to dry maize to the required levels and sometimes ends with infected crops due to humidity caused by the rain and inadequate drying methods. If losses are avoided through enhanced harvesting, postharvest handling (cleaning, drying, and packing), and storage procedures, significant gains in total production and productivity can be obtained in real terms [11]. Farmers and traditional grain processors have been trialling and erroring numerous traditional processes that result in massive losses in stored pulse grains due to bugs and pest infestation [12]. Agriculture is Rwanda's most important economic sector, accounting for a third of the country's GDP and over half of its export profits. As a result, Rwanda's government has prioritized agricultural development, allocating large resources to increase productivity, expand the livestock sector, promote sustainable land management, and establish supply chains and value-added industries [13].

Modernizing subsistence agriculture through a crop intensification program to address food security and increase the country's agricultural production is one of the primary goals of the Economic Development and Poverty Reduction Strategy (EDPRS). Maize, wheat, rice, and beans have been recognized as priority crops, with an emphasis on on-farm consolidation and farm inputs (seeds and fertilizers, mechanization, irrigation, extension services on the use of inputs, and improved cultivation services) [5].

The food produced in many parts of Africa during one harvest period may last for only a few weeks and must be stored for gradual consumption until the next harvest, and seed must be held for the next season's crop. In addition, in a market that is not controlled, the value of any surplus crop tends to rise during the off-season period, provided that it is in a marketable condition [14]. Therefore, the lack of an efficient storage system to maintain the crop in prime condition as long as possible due to poor handling, drying, and storage system increases losses and is inappropriate concerning other factors such as economies of scale, labor cost, availability, building costs, and machinery costs.

Particularly in Rwanda, the postharvest losses are around 16-22 percent for cereals and 11 percent for beans, while the country is targeting to reduce that to 5 percent of losses by 2024. Postharvest losses in grains are estimated to range between 15% and 22%, according to the MINAGRI [15]. As a result of the reduced supply, losses affect both producers and consumers, lowering farmer incomes and increasing customer prices.

The idea of drying crop production with the help of the new technology is not new; this is the case of an IoT architecture and components from an agronomic and technological approach where sensors and machine learning models are used to play a huge role in cropping system simulation programs that was discussed in [13, 16]. Sensors can be embedded into grain storage containers to monitor temperature and humidity; then, the collected data are sent to the cloud platform for processing [17–19]. Smart systems can observe and maintain the storage environment using an Arduino and an Ethernet shield to send data in the MYSQL database and establish connectivity with the sensor node and web server, together with a mobile application developed in an android smartphone, as detailed in [20, 21]. Cloud computing plays a big role in monitoring crops for real-time analysis of data acquired as discussed [22]. Some studies suggest that drying the seed to around 2% moisture content and adjusting the storage temperature and oxygen level of the storage atmosphere can extend the storage longevity of maize grain as demonstrated in [23]. Grain storage can be fully automated using PLC and SCADA to prevent the formation of microorganisms as developed in [24].

Sun dryer's temperature has been monitored and adjusted in accordance with the needs of a particular crop [25], the operation of indirect solar dryers has been examined, and an IoT-based system has been implemented by using deep learning method. Pavan Kalyan et al. [26] discussed alternative wetting and drying methods for crops especially rice, this method brought a tolerance of up to 30-40% reduction of water supply during the main growing period compared to conventional methods, and this contributed to the reduction of human processing tasks since the precision farming approach provides better management of crop. Rehman et al. [27] revised several IoT technology-based techniques used to boost crop yield and save time, done by monitoring farms remotely on real-time basis and through distributed wireless sensor networks for inspection and control. A technical guide for ag-IoT system design and development has been made in [28] for crop, soil, and microclimate monitoring, where in order to convert the labor-intensive job into an automatic, data-driven method in agricultural production, the soil-plant-atmosphere continuum has been monitored automatically at a high spatio-temporal resolution.

Grain storage system has been monitored on real-time basis where several sensors such as DHT11, MQ2, MQ135, and PIR sensors are discussed in [29]; regular updates of the system are done by the Blynk application through notifications so as to ensure online detection, regular updates, and easy maintenance of the system. Information processing and prediction of grain situation in the storage can be done by a host computer placed in control room, and a computer terminal can be placed in the granary for data acquisition while monitoring the grain environmental parameters as detailed in [30].

This research contributes in resolving the maize drying and storage issues faced by farmers by continuously monitoring the corn drying process at every stage and alerting farmers to any critical situations for appropriate action to be taken. Humidity, temperature, and light sensors are incorporated in the drying and storage field, and these are used to transmit data online. This system enables farmers to keep an eye on their corn both locally and remotely. The remote monitoring is done using a computer through ThingSpeak or a smartphone through GSM, and the on-site monitoring is done using a liquid crystal display (LCD).

This paper is organized into four sections. The first section provides the general introduction of the study in which various important topics are discussed such as the background on the current maize drying and storage practice in Rwanda, the problems caused by the lack of a smart maize monitoring system, and the related literature on the existing works and gap identification. The second section discusses the materials and methods used to carry out this research. The results and discussions of the IoT-based real-time maize crop drying and storage monitoring system model are discussed in Section 3, whereas the conclusion, recommendations, and future works are provided in Section 4.

2. Materials and Methods

2.1. Data Collection. In addition to literature exploration, the research team has conducted site surveys to understand the methods used by farmers while drying and storing maize and the challenges that they face while drying and storing maize; the findings from the conducted surveys led to the successful implementation of the solution that responds to the gaps identified on the field.

The research team identified maize farmers' cooperatives and individual maize farmers targeted to collect information relating to posthandling maize activities. During this process, the team has interacted with 7 maize cooperatives from 7 different sectors of Burera District, Musanze District, Nyagatare District, and Gicumbi, in Rwanda. These cooperatives have around 70 members. The surveys were anonymous to let respondents be free to answer to the best of their knowledge and experiences. The samples of respondent farmers were taken from the cold, high hill regions of Rwanda in Musanze, Burera, and Gicumbi. Another sample was taken from the hot, Savana Region of the country in Nyagatare, to have all information on the maize posthandling practices of the two regions.

2.2. System Design. Poor drying of maize gives room for the production of mycotoxins. Therefore, a solution that is dealing with monitoring the storage environment parameters has been thought of. Figure 1 illustrates the block diagram of the system.

As it is illustrated in the above figure, the system has a temperature and humidity sensor used to detect the temperature and humidity in the maize container. Since temperature is one of the products of crop respiration, monitoring the temperature and lowering it as needed can help to reduce the rate of respiration, thereby extending the storage life by reducing the chance of germination. A light-dependent resistor (LDR) has been used for light detection; since light can generate a form of energy that can degrade the food value of food, it is better to store crops in the dark. A microcontroller has been used for processing the data from sensors. For notification, the global system for mobile (GSM) communication is used to give a short message on cell phones when critical parameter conditions are detected. A web dashboard is used as an IoT platform through which the monitoring of the drying and storing parameters of maize grains is done. The on-site notification is done using a liquid crystal display. The output is in the form of notification messages informing the farmers about the real-time maize parameters in the drying and storage process, and their corresponding graphs are displayed on the ThingSpeak platform.

2.2.1. Sensing Part. The IoT-based real-time crop drying and storage monitoring system targets the efficient drying and storage of maize grains. In Rwanda, maize grains are mostly dried in hangars on branches of threes and stored in ordinary packaging containers or oxygen-free plastic bags. The sensors used are the temperature and humidity sensor and light sensor (light-dependent resistor). The following figure illustrates the temperature and humidity sensor and the light sensor connected to the microcontroller. Figure 2 illustrates the sensing part of the system.

While deploying the sensor nodes, the quality of service has been taken into consideration, analysing how well the sensor nodes collect the information from the maize drying and storage space. Commonly, the sensing performance decays as the sensing distance increases. We have adopted a modelling where the point-to-point sensing accuracy varies as a nonincreasing function of the distance or to minimize a negative sensing performance [31]. Below is the formula illustrating the quality of service analysis while deploying sensor nodes in the container.

$$1_{[\mathrm{RS}]}(\|pn-\omega\|)=\begin{cases}1, & \|pn-\omega\|<\mathrm{Rs},\\ 0, & \|pn-\omega\|\leq \mathrm{Rs},\end{cases} \tag{1}$$

where N is the number of sensor nodes, R is the set of real numbers, $P=(p_1, p_2, \cdots p_N)$ are the sensor node

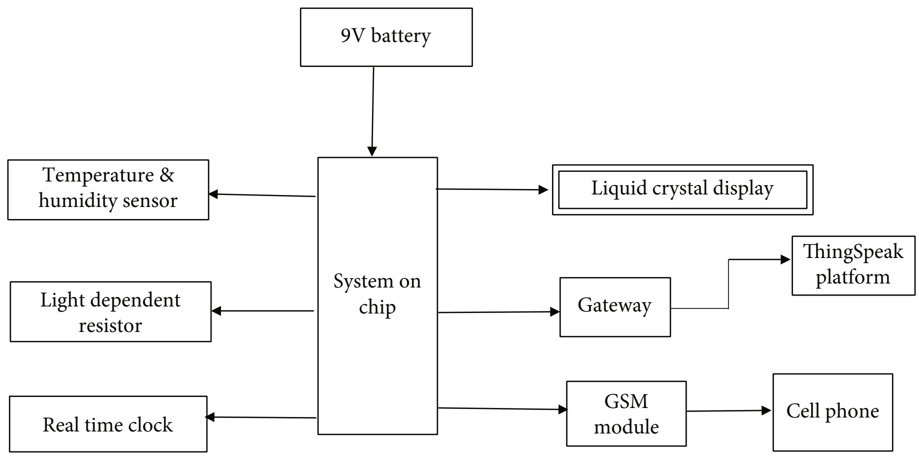

Figure 1: Block diagram of the IoT-based real-time crop drying and storage monitoring system.

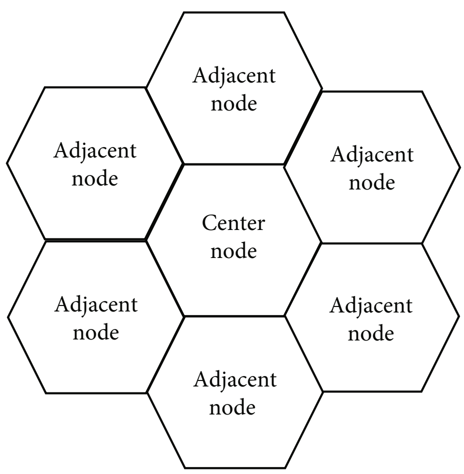

Figure 2: Regular hexagon pattern for sensor node deployment.

locations, $\Omega \subset R^d$ is the target region, $\omega \in \Omega$ is the target point, //.// is the Euclidean distance, $C(.)$ is the sensing accuracy, $D(.)$ is the sensing uncertainty, and Rs is the sensing range.

Additionally, the energy conservation has been analysed; this includes the energy consumed by the sensor nodes to produce local data, the energy consumed to receive data, the energy consumed to transfer data, and the energy consumed when the node is in the dormant state. The connectivity of the sensor nodes has been explored as well [32].

When placing sensor nodes, the communication range and the sensing range were taken into consideration. The Internet of Things-based real-time crop drying and storage monitoring system must continuously check the environmental conditions inside the drying and storing area, and it must even be able to spot dangerous situations so that maize farmers can be informed.

The analysis of temporal changes and geographical differences in the maize drying and storing area is the purpose of the wireless sensor networks. This means that, based on the sensor data gathered by the network, interpolation at unsampled sites is used to provide the spatial distribution of environmental variables. Regular pattern in spatial sampling has been utilized for this purpose since it has been shown to be more dependable and effective than other forms of communication [33]. As seen in Figure 2, the regular hexagon pattern offers at least 6 connections.

The number of sensor nodes has been determined through the area of the grid cell:

$$A^{H} = \frac{\sqrt{3}}{2} d_{ms}^{2}, \tag{2}$$

where A^H denotes the area of the grid cell in the regular hexagon pattern and d_{ms} denotes the maximum separation between two nearest neighbouring nodes.

It is crucial to put sensors and gateways in the corn drying and storage area properly to improve communications and network performance. In order to place each gateway in the optimal location for minimizing the latency of data delivery from sensors to a gateway, genetic algorithms have been applied. Genetic algorithm for distance optimization has been used in this study to better serve the intracluster network by clustering sensors into disjoint clusters and determining the optimal position for each individual gateway. In essence, the gateway is assigned to each cluster and strategically positioned to allow sensors to connect to it with the fewest hops possible. The genetic algorithm's complexity is reduced by the genetic algorithm for distance optimization at the expense of the viability of the solution. Figure 3 illustrates the average delay per packet in seconds versus number of gateways.

Random denotes that the gateway position is randomly picked in the area. Uniform denotes that the deployment area is divided into grids of equal size cells in which the gateway is placed at the centre of a cell. GAHO stands for genetic algorithm for hop count optimization, while GADO is the genetic algorithm for distance optimization, whereas COLA represents the coverage and latency aware positioning scheme. Figure 4 illustrates the sensing parts of the system.

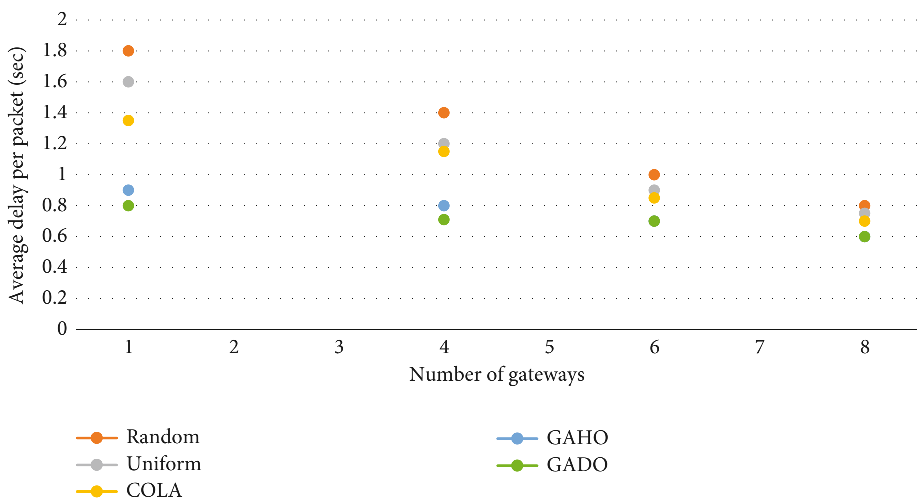

Figure 3: Average delay per packet in seconds versus the number of gateways.

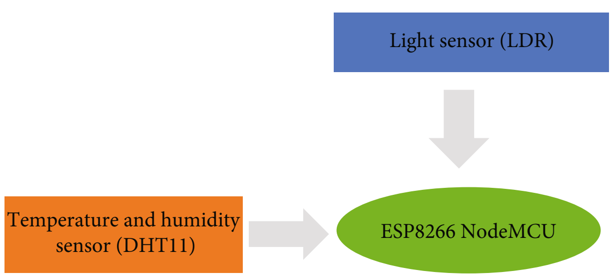

Figure 4: Sensing part of the system.

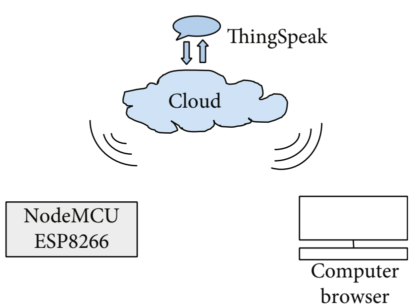

Figure 5: ThingSpeak communication.

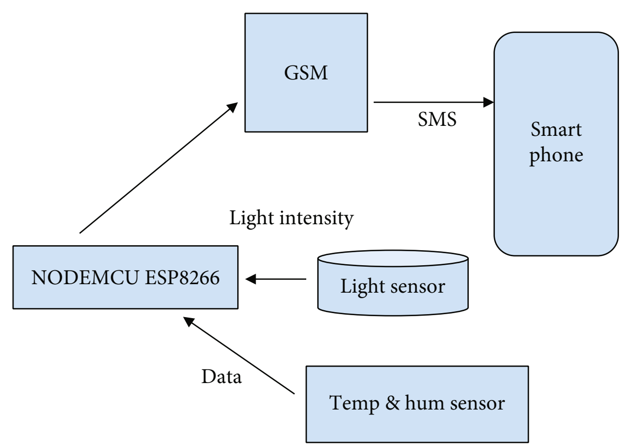

Figure 6: GSM connectivity.

The ESP8266 Wi-Fi module is a self-contained SOC with an integrated TCP/IP protocol stack that allows any microcontroller access to the Wi-Fi network. This board was programmed by using C programming via visual studio code integrated with platform IO.

2.2.2. Wireless Communication System. During the process of strategizing and architecting the wireless network design, before choosing the wireless network to be used, several parameters have been considered including the coverage range, the capacity, the application, the network security, the network simplicity, the redundancy, the network integration, and the network management. In the network planning, the network infrastructure available in the maize drying and storing place, the application, the network performance, and the capacity requirements of the maize storing space have been taken into consideration. In this work, Wi-Fi-enabled device, namely, the ESP8266 module, which is a low cost and branded as ultralow power, has be identified as a preferable wireless network for this application. With second-scale transmission intervals and 2-4 days recharge periods on a 1000 mAh battery, the ESP8266 module provides suitable for powered Internet of Things applications among which this IoT-based maize drying and storage monitoring falls [34]. Additionally, the wireless networks' built-in sleep modes have been examined, and the effect of infrastructure factors such as beacon interval and DTIM duration on energy usage has been taken into account. Additionally, a claim regarding the coverage area has been made and the exploration of the packet delivery ratio and received signal strength as a function of location and module antenna orientation.

End users can receive data collected from the field and real-time monitoring from any location utilizing different types of wireless or cable communication protocols, thanks to IoT technology. After collecting data from a different site, the data were sent to the developed cloud platform by using Message Queuing Telemetry Transport (MQTT).

Figure 7: Field visits to maize farmers for data collection.

ThingSpeak is a Ruby-based open-source program that allows users to speak with Internet-connected gadgets. By giving an API to both devices and social network websites, it makes data access, retrieval, and logging easier. Clients can use the ThingSpeak MQTT broker to update and receive updates from channel feeds via the ThingSpeak IoT platform. MQTT is a TCP/IP sockets or web socket-based publish/subscribe communication mechanism. A real-time monitoring of temperature, humidity, and air quality can be done using ThingSpeak cloud, as demonstrated in [35]. Sensor data is stored in a ThingSpeak cloud for easy view of data from a remote location as illustrated in [36]. As shown in Figure 5, data is transmitted to ThingSpeak cloud platform through the Wi-Fi module incorporated in the NodeMCU ESP8266. Data are visualized on a computer screen for monitoring or further analytics.

In addition to the monitoring done on the cloud platform, the system sends SMS notifications using GSM to the farmer in case critical parameters are sensed. Figure 6 shows the GSM connectivity between sensor node and mobile phone. A dual-band GSM/GPRS engine called Sim900A that operates on the frequencies EGSM 900 MHz and DCs 1800 MHz has been used for this purpose [37]. The GPRS coding schemes Cs-1, CS-2, CS-3, and CS-4 are supported by Sim9909A's GPRS multislot class 10 functionality. Sim900A is built using energy-saving techniques, resulting in a sleep mode current usage of under 1.0 mA. For data transfer applications, it integrates the TCP/IP protocol and enhanced TCP/IP AT commands [38].

As it was stated in the methodology, the research team conducted site surveys to collect data from different farmers using a questionnaire that has been designed to target helpful responses that contributed to the solution development. This can be seen in Figure 5, where the first image from the left side shows the maize harvest dried on hangars for about two months, wait for full dryness. The second image illustrates the dryness testing method which is mostly used by maize farmers in Rwanda by using a bottle which contains salt, where a sample of maize grains is inserted in the bottle; if no grain leans on the bottle surface when the bottle was shaken, then full dryness is confirmed. The third and fourth images show interviews conducted to different maize farmer cooperatives for clear understanding of the drying and storing process of maize; here, a questionnaire was elaborated, and it was used along the whole data collection process.

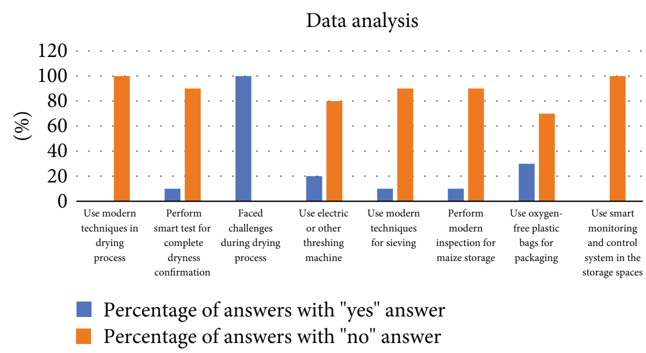

Figure 8: Data analysis chart of the findings from the field visit.

The maize drying process in Rwanda is done in hangars, where maize corns are hanged on wooden horizontal bars as shown in Figure 7, for a period of 2 to three months, but there is no smart system to monitor the drying progress of the maize grain, and no technological test is performed to ensure complete dryness of the maize grains before being removed from the drying place for storage. After drying, the maize harvest is stored in plastic containers which are hermetically closed to avoid oxygen to enter into the bags and are placed in a warehouse on the floor or on wooden bars placed on the floor, but the parameters under which the storage is made are not smartly monitored at all; this leads to maize infections when the maize is stored for more than a month. Most of the time, farmers sell immediately the maize harvest without storing it fearing these infections; however, they sell the harvest at a very low price which does not compensate the investment made while cultivating the maize plantation.

As illustrated in Figure 8, questions like the following have been proposed: Are there any modern techniques used to dry maize harvest? Is there any smart test performed to confirm the total dryness of maize? Are there any challenges faced during the maize drying process? Do you use electric or other threshing machines for a fast and safe threshing process? Do you use modern techniques for sieving? Is there any modern inspection of mycotoxins' during the drying process? Do you use oxygen-free plastic bags for maize grains packaging and storing? Is there any monitoring and control system used to ensure a good storing environment of maize? The results from the responses of farmers about the above questions were made to develop the following IoT-based solution.

FIGURE 9: On-site monitored readings from the liquid crystal display.

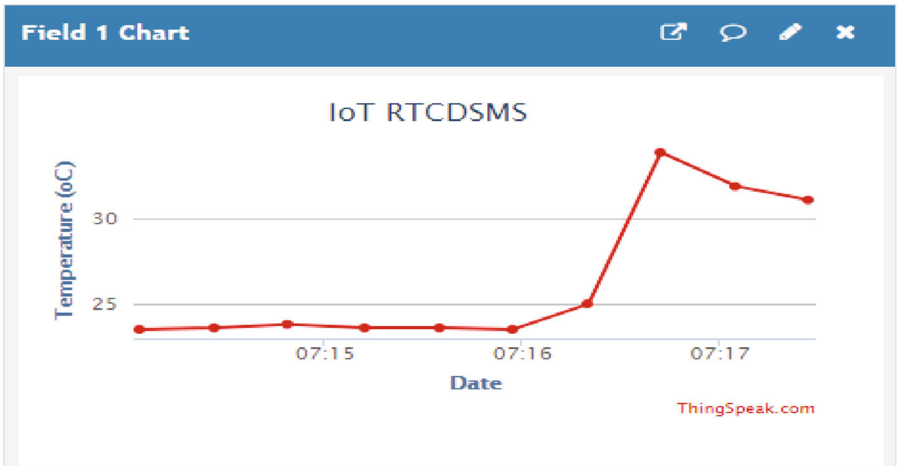

FIGURE 10: Temperature readings on the ThingSpeak.

During the conversation with the maize farmers, it has been found that

(i) 100% of the maize farmers do not use modern techniques in drying process and they do not use smart monitoring and control system in the storage spaces

(ii) 90% of the maize farmers do not perform smart test for complete dryness confirmation, they do not use modern techniques for sieving, and they do not perform any modern inspection for maize storing

(iii) 80% of the maize framers do not use electric or other threshing machines

(iv) only 30% of the maize farmers use oxygen-free plastic bags for packaging

The information gathered indicates that there are not enough technical methods being utilized to dry and store the crop of the labyrinth, which causes the maize to degrade while it is being dried or stored. This can be eliminated by utilizing a smart maize drying and storing system to monitor the environmental conditions in which the harvested maize is kept, by assuring routine monitoring and prompt notice in the event that the conditions exceed the safe range for storage and drying.

3. Results and Discussion

In a controlled environment, the IoT-based real-time crop drying and storage monitoring system solution was put to the test to check how accurate it was and how well it can monitor the whole maize storage conditions. Data was collected as well as comparison tests to verify the accuracy and durability of several types of sensors that would be used in the final IoT-based real-time crop drying and storage monitoring system product.

The results from the prototype are the temperature, humidity, and light which are monitored through ThingSpeak. The other result is an SMS notification from the deployed IoT system located in maize drying spaces and storing containers. When the temperature goes out of the range of 5°C to 30°C and the humidity exceeds the range of 18 to 30%, a notification message is delivered to the maize farmer's cell phone. To prevent infection, an optimal illumination intensity between 50 and 90 lux is maintained. Figures 9–12 show the collected temperature, humidity, and light from a maize farmers' cooperative in the BURERA district, as monitored through the ThingSpeak cloud platform.

In case the farmer has been notified about the critical conditions detected in the maize drying space, some actuators among those installed in the system are turned on, in accordance to the parameter's level sensed. Those actuators include fan, heater, humidifier, and a bulb lamp. This is done in order to maintain the environmental parameters at the maize preferred level as mentioned above.

The developed system adds value to the existing systems that have been already developed for maize storage monitoring systems. Various systems have been developed for maize storage container monitoring systems where several sensors were deployed and different cloud platforms were used for analysis purposes as detailed in the related works. As it has been noticed through the site survey, the efficient handling of maize postharvest should start from monitoring the drying parameters under which the maize is placed and then move to the storing place too,

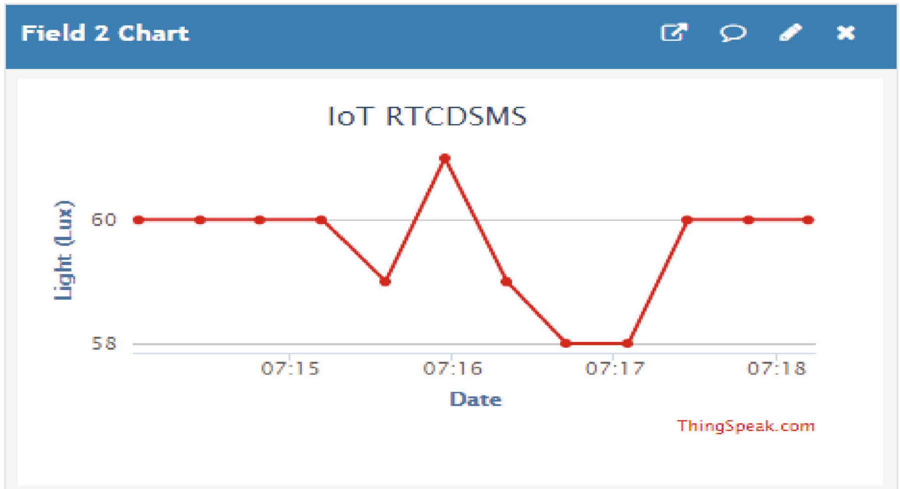

FIGURE 11: Light intensity readings on the ThingSpeak.

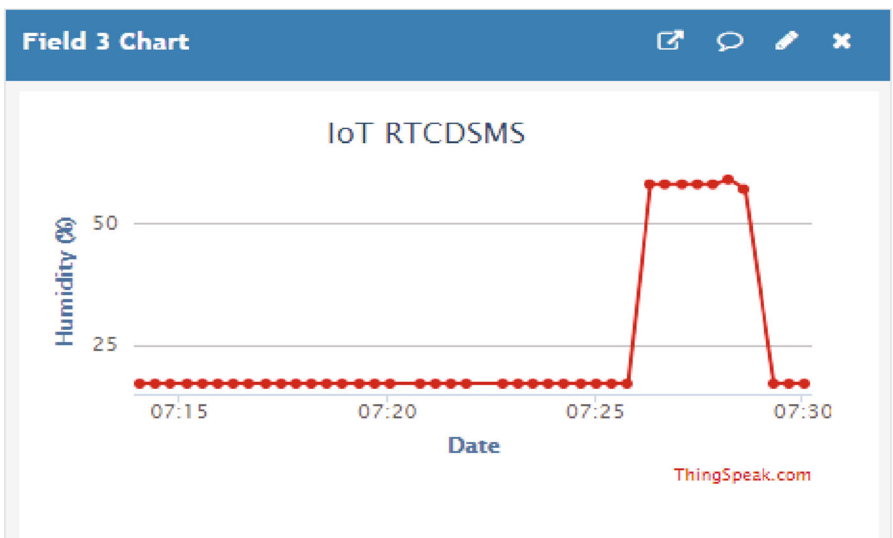

FIGURE 12: Humidity readings on the ThingSpeak.

which is what this system is dealing with and further avail notifications to farmers in case of critical environment conditions. This goes together with the use of a cloud platform ThingSpeak through which real-time monitoring and analytics are done. This research complies with the climate situation in Rwanda, and the affordability of the system by farmers has been taken into consideration. Given that many of the farms in Rwanda do not have access to electricity, a solar-powered system has been proposed for the system to operate.

Combining cutting-edge sensors with IoT as done in this paper and as discussed in [27] contributes in the improvement of traditional farming methods. In this work, wireless sensor networks have been incorporated in the maize drying and storage area to ensure complete drying and adequate maize storage leading to precision farming. The developed system is very flexible especially in customized due to the sensors and main control board used, as it has been analysed in [28] where wireless sensors and main control boards have been compared in terms of flexibility and response time in accordance to the application.

Different systems have been designed aiming at improving crop production as discussed in the literature; however, this developed system comes to add-on to the existing systems, such as in the work [17] where humidity and temperature are monitored in seed storage containers and data is further sent to the cloud as done in this paper. The novelty in this paper comes to the monitoring process which starts at the early stage of drying stage since the drying process affects the storage results if not well done; this has been observed in other works like in [20] as well.

In the work [29], the Blynk application has been used to ensure remote monitoring of the grain storage, but in order for this application to function, a common Internet connection must be made between the device hosting the Blynk application, which is typically a smart mobile phone, and

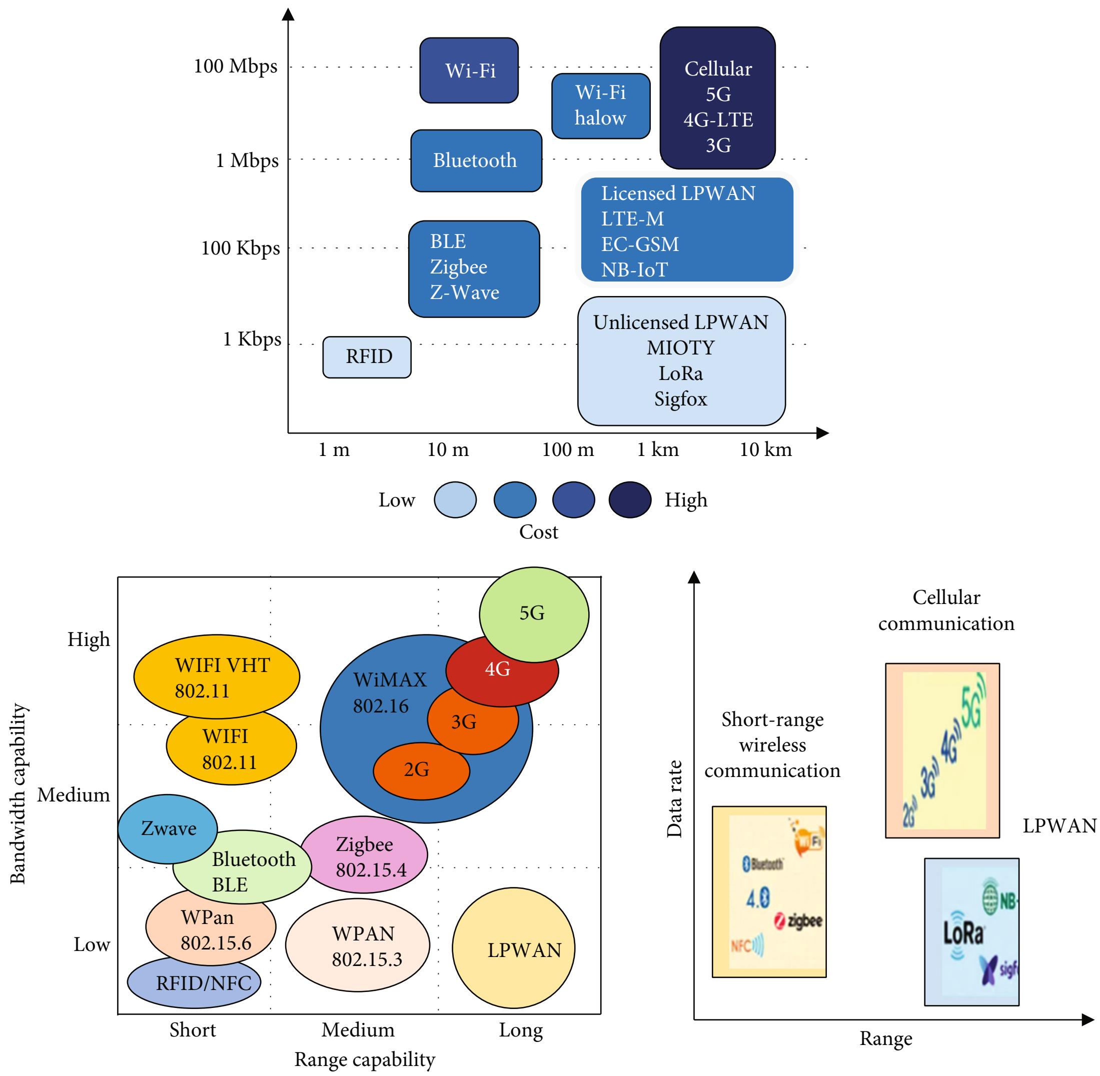

Figure 13: LoRa vs. other IoT wireless technologies.

the actual system installed in the grain container. Because the cloud platform has no distance restrictions and additional analytics features and does not require a shared Internet network between the IoT circuit deployed in the containers and the computer where the cloud platform is located, this system has used it to monitor the maize remotely.

The developed system responds to the existing gap in the conventional drying method used, as there was no way to monitor the parameters under which the maize crop is dried, and the farmer could not get the maize drying status unless he/she relies to visual inspection on the field, even if such inspection is not adequate.

Several farmer field schools are being organized by the research team for the system usage and maintenance awareness. Further research can be made to automatically control the environment parameters accordingly. The proposed drying system enhances quality production of maize due to the fact that the farmer can monitor the maize storage and take decision according to the obtained notifications of the environmental parameters.

IoT-based storage systems are extremely heterogeneous in terms of sensors and communication technologies. For example, when several platforms coexist and data comes from various subsystems, different communication technologies are integrated. LoRa platforms can be utilized with Zigbee to implement hybrid communications managing various sensor clusters in this Internet of Things-based crop drying and storage system or with an IEEE 802.11s-based system to create mesh network topologies [39].

Future iterations of this study may take into account the challenges and opportunities associated with the integration of many technologies, such as the cloud, IoT, and software-defined networking, as discussed in [40, 41]. LoRa technology can be used if a long-range connection is intended for farmers who are positioned distant from the corn drying and storage system since it enables the construction of an autonomous network that satisfies the low-power and long-range communication requirements [42]. Before making this decision, though, it is important to understand the limitations of LoRa, which include the downlink channel's latency, energy management, heterogeneity and interoperability of the devices, data management, and scalability. The aforementioned issues can be resolved by utilizing machine learning algorithms, which will also increase LoRa's performance and coverage [43].

Furthermore, IoT-based agricultural-based storage systems can benefit from interoperability, thanks to platforms like FIWARE, Cayenne, and mySense. The Industry 4.0-based method, which integrates several protocols to fulfil the needs of automating, computing, and technology processes, can help these solutions outlined above [44].

5G connectivity will enable huge data transfer volumes with low latency, enabling futuristic scenarios [45]. This might produce positive effects for agricultural technology applications. Figure 13 illustrates the comparison between LoRa and other IoT wireless technologies.

Wi-Fi has a higher bandwidth but a lower battery life and shorter range, which makes it unsuitable for dispersed IoT devices. Given its low-power and long-range nature, LoRa would be a good choice to make in the event that the available IoT-based crop drying and storage monitoring system needs to be used for a long-range data transmission between the storing place and the remote position of the farmer. Though it struggles to send large data, it strives at sending small packets of data like the temperature and humidity, which is the case of this study.

4. Conclusions

The findings of this study indicated that there are many challenges associated with the current drying and storing methods of maize grains. These include the manual traditional methods of monitoring maize grains in the drying and storage spaces and the lack of a smart on-site and remote monitoring system of the grains' drying and storing parameters. The developed IoT-based real-time monitoring system was found to be a reliable approach to address those challenges due to its ability to collect temperature, humidity, and light intensity and avail the notifications when the set ranges of these parameters. An IoT monitoring platform has been designed to help farmers view the temperature, humidity, and light data anytime and anywhere. Additionally, a GSM module has been added to send a notification to farmers in case of any temperature, humidity, or light excursion during the drying and storage process.

Data Availability

The data used to support the findings of the study are available from the corresponding author upon request.

Disclosure

This research has been conducted as a thesis in the African Centre of Excellence in Internet of Things to fulfil the requirements of the master's degree certification, as found in [46].

Conflicts of Interest

The authors declare that they have no known competing financial or personal relationship that could be viewed as influencing the work reported in this paper.

Acknowledgments

We thank the Regional University Forum for Capacity Building in Agriculture (RUFORUM) for supporting this work under the grant "RU/2020/Post Doc/03."

References

[1] MINAGRI, *Republic of Rwanda Ministry of Agriculture and Animal Resources*, 2021.

[2] E. Mabaya, C. Urinzwenimana, and J. Whiting, *Rwanda Country Report 2021*, 2021.

[3] KPMG, *Industrial Master Plan for the Agro-Processing Subsector (2014-2020) Ministry of Trade and Industry (MINICOM)*, p. 114, 2014.

[4] C. Ngaboyisonga, A. Nyombayire, F. Nizeyimana, and P. Mutangana, "The status of maize seed producers in Rwanda," vol. 2009, pp. 1–12, 2011.

[5] F. Y. Pulat Batirbaev, T. Y. Kim, R. Ma'ani, R. Shim, J. Singer, and M. Snyder, *Maize in Rwanda: a value chain analysis*, p. 45, 2013.

[6] U. B. Mahadevaswamy, K. M. Megha, A. V. Srivatsa, A. G. Jain, and B. B. Rani, "Food Grain Storage Monitoring System," *International Journal of Engineering Research & Technology*, vol. 9, no. 12, pp. 189–196, 2021.

[7] G. District and M. M. Plant, *Improving Firm-Farm Relationship in Maize Production in Rwanda. Case Jeanne Umutoni*, 2013.

[8] M. A. Dandago, L. Kitinoja, and N. Abdullahi, "Commodity system assessment on postharvest handling, storage and marketing of maize (Zea mays) in Nigeria, Rwanda and Punjab, India," *Journal of Horticulture and Postharvest Research*, vol. 4, no. 1, pp. 51–62, 2021.

[9] C. Bucagu, A. Ndoli, A. R. Cyamweshi, L. N. Nabahungu, A. Mukuralinda, and P. Smethurst, "Determining and managing maize yield gaps in Rwanda," *Food Security*, vol. 12, no. 6, pp. 1269–1282, 2020.

[10] N. Agriculture, "Ministry of agriculture leaflets," *Nature*, vol. 138, no. 3492, pp. 583–583, 1936.

[11] A. Kathiresan, *Strategies for sustainable crop intensification in Rwanda. Shifting focus from producing enough to producing surplus*, Ministry of Agriculture and Animal Resources, Rwanda, 2011.

[12] C. Karthikeyan, D. Veeraragavathatham, D. Karpagam, and S. Ayisha Firdouse, "Traditional storage practices," *Indian Journal of Traditional Knowledge*, vol. 8, no. 4, pp. 564–568, 2009.

[13] K. Giertz, A. Mudahar, M. S. Gray, G. Rubaiza, R. Galperin, and D. Suit, *Agriculture global practice technical assistance paper: Rwanda agriculture sector risk assessment*, vol. 96290-RW, World Bank, 2015.

[14] S. Al-Badri, "Grain crop drying, handling, and storing," 2019.

[15] K. (CARANA C. Van Dusen, N (CARANA Corporation); Beyard, "Post-harvest Handling and Storage (phhs) Project," 2013.

[16] X. Feng, F. Yan, and X. Liu, "Study of wireless communication technologies on Internet of Things for precision agriculture," *Wireless Personal Communications*, vol. 108, no. 3, pp. 1785–1802, 2019.

[17] R. H. Prasadh and S. H. A. Prof, "Enhancement of IoT based smart salvation and monitoring devices for agriculture," *International Journal of Recent Trends in Engineering and Research*, vol. 7, pp. 204–209, 2018.

[18] J. S. B. Shilpa and G. M. Sheeba, "Automated Real Time Monitoring for Food Grain Storage," *International Journal of Pure and Applied Mathematics*, vol. 118, no. 24, pp. 1–13, 2018.

[19] I. Oluwaseun, "Iot-Based System Of Physical Environment Factors Into Monitoring Of Maize Storage," *The Journal of Multidisciplinary Engineering Sciences Studies*, vol. 7, no. 5, pp. 3870–3877, 2021.

[20] A. S. Kumar, G. Suseendran, D. Akila, and C. Priya, "Computerized agricultural storage manipulation system using IoT techniques," *International Journal of Technical Innovation in ModernEngineering & Science*, vol. 4, no. 12, 2018.

[21] M. Sajjad, H. Talpur, S. Khan, A. Oad, R. Sarwar, and A. H. Soomro, "IoT Based Grain Storage Monitoring with Android Application," *International Journal*, vol. 10, no. 2, pp. 1356–1361, 2021.

[22] S. Kundu, *Climate Change and Indian agriculture: Challenges and Adaptation Strategies Editors*, 2020.

[23] J. G. Green, *High Temperature Storage of Dry Maize*, Iowa State University ProQuest Dissertations Publishing, 1961.

[24] K. Kalaivani, V. Anjalipriya, and P. Surendar, "Monitoring and control of grain storage using PLC," *International Journal of Engineering Research and Technology*, vol. 1, no. 3, pp. 282–288, 2012.

[25] B. B. Sharma, G. Gupta, P. Vaidya, S. Basheer, F. H. Memon, and R. N. Thakur, "Internet of Things-based crop classification model using deep learning for indirect solar drying," *Wireless Communications and Mobile Computing*, vol. 2022, Article ID 1455216, 11 pages, 2022.

[26] G. P. Kalyan, M. Bingipalli, and N. B. Patil, "Alternate wet drying method in paddy cultivation in India by using soil moisture sensors: a review," *The Pharma Innovation Journal*, vol. SP-11, no. 5, pp. 292–296, 2022, http://www.thepharmajournal.com.

[27] A. Rehman, T. Saba, M. Kashif, S. M. Fati, S. A. Bahaj, and H. Chaudhry, "A revisit of Internet of Things technologies for monitoring and control strategies in smart agriculture," *Agronomy*, vol. 12, no. 1, p. 127, 2022.

[28] N. Chamara, M. D. Islam, G. Bai, Y. Shi, and Y. Ge, "Ag-IoT for crop and environment monitoring: past, present, and future," *Agricultural Systems*, vol. 203, article 103497, 2022.

[29] A. D. A. K. S. H. S. Wagh, "Intelligent grain storage management system based on IoT," *International Journal of Science and Research*, vol. 8, no. 3, pp. 1749–1752, 2019.

[30] L. K. Hema, S. Velmurugan, D. N. Sunil, S. Thariq Aziz, and S. Thirunavkarasu, "IOT based real-time control and monitoring system for food grain procurement and storage," in *International Conference on Mechanical, Electronics and Computer Engineering 2020*, vol. 993, Kancheepuram, India, 2020no. 1.

[31] Z. Wang, "Node deployment optimization in wireless sensor networks," *Journal of Physics: Conference Series*, vol. 1650, no. 3, 2020.

[32] H. Zhang and C. Liu, "A review on node deployment of wireless sensor network," *International Journal of Computer Science Issues*, vol. 9, no. 6, pp. 378–383, 2012, http://ijcsi.org/papers/IJCSI-9-6-3-378-383.pdf.

[33] L. Hui, M. Zhijun, and S. Yuanyuan, "Sensor nodes placement for farmland environmental monitoring applications," in *2009 5th International Conference on Wireless Communications, Networking and Mobile Computing*, pp. 1–4, Beijing, China, 2009.

[34] D. Guimar, "IEEE International Conference on Emerging Technologies and Factory Automation, ETFA," in *IEEE International Conference on Emerging Technologies and Factory Automation, ETFA*, pp. 784–791, Stuttgart, Germany, 2016.

[35] D. Parida, A. Behera, J. K. Naik, S. Pattanaik, and R. S. Nanda, "Real-time environment monitoring system using ESP8266 and thingspeak on Internet of things platform," in *2019 International Conference on Intelligent Computing and Control Systems (ICCS)*, pp. 225–229, Madurai, India, 2019.

[36] B. A. Tapakire, "IoT based smart agriculture using Thingspeak," *International Journal of Engineering Research*, vol. V8, no. 12, pp. 270–274, 2019.

[37] T. G. Shield, A. Board, and T. G. Shield, "GSM shield SIM900," *GSM Shield SIM900*, vol. 3, pp. 1–8, 1800.

[38] R. B. Babu, C. JonathanSoumith, T. C. Lakshmi, and R. K. Rao, "GSM Based Agriculture Monitoring and Controlling System," *Global Journal of Computer Science and Technology*, vol. 15, no. 2, pp. 43–45, 2015.

[39] A. Pagano, D. Croce, I. Tinnirello, and G. Vitale, "A survey on LoRa for smart agriculture: current trends and future perspectives," *IEEE Internet of Things Journal*, vol. 10, no. 4, pp. 3664–3679, 2023.

[40] D. Saadia, "Integration of cloud computing, big data, artificial intelligence, and Internet of Things," *International Journal of Web-Based Learning and Teaching Technologies*, vol. 16, no. 1, pp. 10–17, 2021.

[41] V. T. Truong, A. Nayyar, and S. A. Lone, "System performance of wireless sensor network using LoRa-Zigbee hybrid communication," *Computers, Materials & Continua*, vol. 68, no. 2, pp. 1615–1635, 2021.

[42] E. Kokten, B. C. Caliskan, S. Karamzadeh, and E. G. Soyak, "Low-powered agriculture IoT systems with LoRa," in *2020 IEEE Microwave Theory and Techniques in Wireless Communications (MTTW)*, pp. 178–183, Riga, Latvia, 2020.

[43] F. Cuomo, D. Garlisi, A. Martino, and A. Martino, "Predicting LoRaWAN behavior: how machine learning can help," *Computers*, vol. 9, no. 3, p. 60, 2020.

[44] Y. Liu, X. Ma, L. Shu, G. P. Hancke, and A. M. Abu-Mahfouz, "From Industry 4.0 to agriculture 4.0: current status, enabling technologies, and research challenges," *IEEE Transactions on Industrial Informatics*, vol. 17, no. 6, pp. 4322–4334, 2021.

[45] M. van Hilten and S. Wolfert, "5G in agri-food - a review on current status, opportunities and challenges," *Computers and Electronics in Agriculture*, vol. 201, article 107291, 2022.

[46] I. Viviane, *IoT based real-time crop drying and storage monitoring system*, University of RWANDA-African Center of Excellence in IoT, 2021, https://aceiot.ur.ac.rw/?IoT-based-real-time-crop-drying-and-storage-monitoring-system.