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Abstract

Purpose: Unpredictable and rapid change in weather patterns has great impact on agricultural activities, especially for precision agriculture that results in worsened water resources availability, decreased soil fertility, use of pesticide as well as decreased yield productivity. In attempt to alleviate these challenges, this study aims at developing a real-time weather and farm field data driven Artificial Intelligence (AI) and Internet of Things (IoT) system that analyze, manage and schedule irrigation and fertigation as well as enabling farmers to interact with their farms via Smart phone or PCs to optimize energy and water resources.

Methodology: The system employs weather condition monitoring sensors such as atmospheric pressure, air temperature, air humidity and wind speed for collecting real-time farm field data and uses Fuzzy Inference System (FIS) to predict rainfall rate at farm area for 24 hours period. The system also gathers field data such as soil moisture content and soil nutrient content and uses the Machine Learning (ML) algorithms to predict the time for irrigation and fertigation. By combining weather and farm field data, the system schedules the irrigation and fertigation activity. In addition, the mobile application is developed for the farmers to interact, control and monitor the farming activities and the data is presented to the farmers in both graphical and numerical formats.

Findings: The system prototype deployed and tested in the two hectors Maize farm proved that 55% of water, 51% of energy and 20% of fertilizer were saved as well as increases in 20% of Maize yield production compared to previous season.

Recommendations: Since the current irrigation and fertigation practices are based on predetermined time of the day and threshold values for automatic irrigation, this solution introduced the new concept of real-time and short-term weather forecasting that enables farmers to balance the irrigation period and weather pattern for water and fertilizer resources optimization.

Keywords: *AI, IoT, Weather Prediction, Smart Irrigation, Smart Fertigation, Fuzzy Logic*

1.0 INTRODUCTION

The world is facing significant challenges in meeting the growing demand for food, especially in developing countries including Rwanda where 90% of its population depends on agriculture and its population growth is rapidly increasing while farmlands are getting reduced as cities expand[1][2]. However, the agricultural sector in Rwanda is facing serious challenges including climate change, water scarcity, poor soil fertility and the need to improve resource management for sustainable farming practices[3]. As a result, there is an urgent need to develop innovative solutions that can improve agricultural efficiency and sustainability. One such solution is the integration of Artificial Intelligence (AI) in conjunction with Internet of Things (IoT) technologies into irrigation and fertigation systems, coupled with advanced weather prediction capabilities that holds great potential to enhance agricultural efficiency and sustainability [4].

Traditional irrigation practices in Rwanda often suffer from inefficiencies due to fixed schedules and manual assessments, leading to the wasteful use of water and fertilizers and decreased crop yields[5]. The manual method used in irrigation involves building canals which supply uniformly water from water resources or use of water pumps for spraying water evenly in the field and not only much water is wasted but also is time consuming and requires much more manpower[6]. inappropriate fertilizer application due to Lack of knowledge and awareness of the farmers, resulting in either overuse or underuse, both of which can have negative impacts on crop productivity and the environment[7]. Additionally, unpredictable weather patterns, such as irregular rainfall distribution, can further exacerbate the challenges faced by farmers, making it crucial to adopt intelligent and automated systems that optimize irrigation and fertigation processes while considering real-time weather conditions[8].

In Rwanda, the Ministry of Agriculture and Animal Resources (MINAGRI) in collaboration with other stakeholders, developed a national ICT4RAg strategy that recognizes the achievements, challenges, and opportunities present in mainstreaming ICT in Agriculture[9]. with the digitalization and automation applications in agricultural production processes, the reduction in cost and improved efficiency and computational power of electronic systems like use of autonomous robotic systems, wireless sensor network, IoT devices, and the advances in AI and machine learning are gaining popularity[10][11].

With machine vision, there is advancement in understanding, modelling and crop mapping by hyperspectral remote sensing using ground-based, truck-mounted, airborne, and space borne sensors[12]. Also, innovative technology solutions such as satellite tracking and aero monitoring can support large scale digital farming, strengthen adaptation to climate risks, enhance disaster preparedness and aid effective planning and management of agriculture practices in urban Africa[13].

This paper aims to explore the concept of smart irrigation and fertigation with weather prediction technology, its applications in agriculture and its potential for enhancing agricultural sustainability. The AI and IoT technologies based on DL and Fuzzy Logic System design with mobile application are developed as well as hardware components are presented. Furthermore, the system prototype is developed and deployed on the field and research findings that demonstrate the effectiveness of smart irrigation and fertigation are discussed. By embracing smart irrigation and fertigation systems with weather prediction technology, farmers can overcome traditional limitations, improve crop yield, conserve resources, and contribute to sustainable agriculture in an era of climate change and water scarcity.

Related Works

This section of the study presents the up-to-date works done related to the use of technology in agriculture especially in irrigation; IoT based weather prediction application in agriculture is presented followed by use of IoT technology in irrigation and fertigation and finally application of AI in conjunction with IoT in irrigation and fertigation is discussed.

AI systems with sensors are used for collecting weather data and predict its future petters for decision making. Adaptive-neuro Fuzzy Inference System based rain prediction model was developed in [14], [15] and the study in [16], [17] Recurrent Neuro Network rainfall prediction model was proposed for irrigation purpose. These AI based approaches collected weather data including temperature, humidity, rainfall, wind speed and solar radiation and processes them for the purposes of predicting the probable amount of rainfall. The real-time weather prediction system needs to be integrated into irrigation and fertigation system for optimizing the irrigation scheduling[18].

IoT technology has been increasingly employed in irrigation and fertigation practices to enhance resource management, optimize crop growth, and improve overall agricultural productivity. Soil moisture sensors and actuators have been used in [19], [20][21] for automatic irrigation but they are based only on threshold values of the moisture in the field. A system consisting of soil moisture sensors, soil temperature sensors, a Raspberry Pi as the MCU, and a water pump is proposed for automatic irrigation monitoring[22]. Smart phones was used to communicate in this solution and the amount of water they require at different phases of growth are taken into account in the solution so that the field is irrigated in accordance with the calculated water need by the plant [23][24]. The integration of IoT devices, sensors, and data analytics enables real-time monitoring, data-driven decision-making, and automated control in irrigation and fertigation systems as developed in [4][21][25]. Soil condition-based Irrigating alone to meet the water requirements of the plants may not result in the appropriate levels of moisture required, the weather patter variation also have to be considered.

Wi-Fi is a widely used wireless communication technique. Many agricultural monitoring systems, such as the one presented in[26] , employ Wi-Fi to communicate among various agents of their designs. They demonstrated a Wi-Fi wireless sensor network for farm monitoring, with nodes collecting data on temperature, humidity, light, soil moisture, and water content. The data was also sent to a server further analysis. As a result, using Wi-Fi coverage in various agricultural settings is of tremendous interest. The research in[26][27], reported a method for estimating the location of wireless nodes based on signal intensity. The IEEE 802.11 b/g standard was used in the locations including urban regions, rural areas, woodlands, and plantations. However, Wi-Fi requires more internet infrastructure when deployed in remote area.

WSN technology is widely used in agriculture as the study in [27], proposes an effective methodology that uses WSN as a data gathering tool and a decision support system (DSS) to assist farmers with manual or automated watering processes. WSN nodes are placed in fields to detect and report numerous plant-growth-related factors such as moisture, salinity, pH, temperature, air humidity, and wind direction, allowing farmers to make informed decisions. DSS examines a variety of indicators to identify water-stressed areas, which it then notifies farmers. The adoption of this technology lowered the amount of water used by farmers and the amount of work they had to undertake[28].

2.0 METHODOLOGY

This study focused on designing an AI-based solution for farmers from a human development perspective since the solution was designed according to the needs of the farming activities. Considering the nature and characteristics of this study, the research setting was framed within the general methodology of Design Science Research (DSR). It started from understanding the problem domain (by exploring soft cases) and ended with (a design case) the implementation and evaluation of a system. Thus, it provided a tentative solution to the problems as found and analyzed in earlier phases.

The system was designed in three main stages including determination and prediction of moisture and nutrient content in the soil using ML model, weather prediction using FIS model as well as irrigation and fertigation scheduling based on FIS model.

Machine Learning (ML) Model

The ML model was developed to determine the current and predict the future moisture and nutrient content level in the soil. The model followed the normal steps undertaken in any machine learning algorithm. It began with collecting and cleaning data for the purpose of preparation for training and then converted into JSON format and uploaded into the cloud-based machine learning platform. The data was also separated into validation set and training sets. The data was then pre-processed so as to generate features for training. After pre-processing the machine learning model was designed and the inputs to the model training was the soil moisture level and soil nutrient content. The data was trained and validated to get the ML model for the output being classification whether there is stress condition in the soil or adequate nutrient content in the soil for accurate decision making.

Fuzzy Inference System

A Fuzzy Inference System (FIS) is a computational model that uses fuzzy logic to make decisions or predictions based on input data. Firstly, real-time weather condition parameters including Air temperature, relative humidity, wind speed and atmospheric pressure were collected and fed to the If-Then rule based FIS for rainfall patterns prediction within 24 hours.

Decision Support System: The output from weather condition prediction of FIS combined with soil condition prediction from ML system were integrated into decision support systems for irrigation and fertigation management. This FIS provides intelligent recommendations for irrigation and fertigation practices. Farmers can utilize these recommendations to make decisions about water and fertilizer management, optimizing resource utilization and crop yields.

System Design and Testing

This section presents the proposed embedded system level design, testing and obtained results. The architecture of the system is first presented and described, followed by the system artificial intelligence modeling including Machine Learning model for irrigation and fertigation decision making, Fuzzy logic system for weather forecasting and finally the whole smart irrigation and fertigation is simulated in MatLab software.

Embedded System Architecture

The embedded system comprises of hardware and software components. The system hardware includes all physical components such as Input sensors, processors and actuators that work together to achieve the precision irrigation and fertigation. The embedded software tools are used to manage and make hardware components function as programmed and that includes Python for ML algorithm and MatLab for Fuzzy logic simulation.

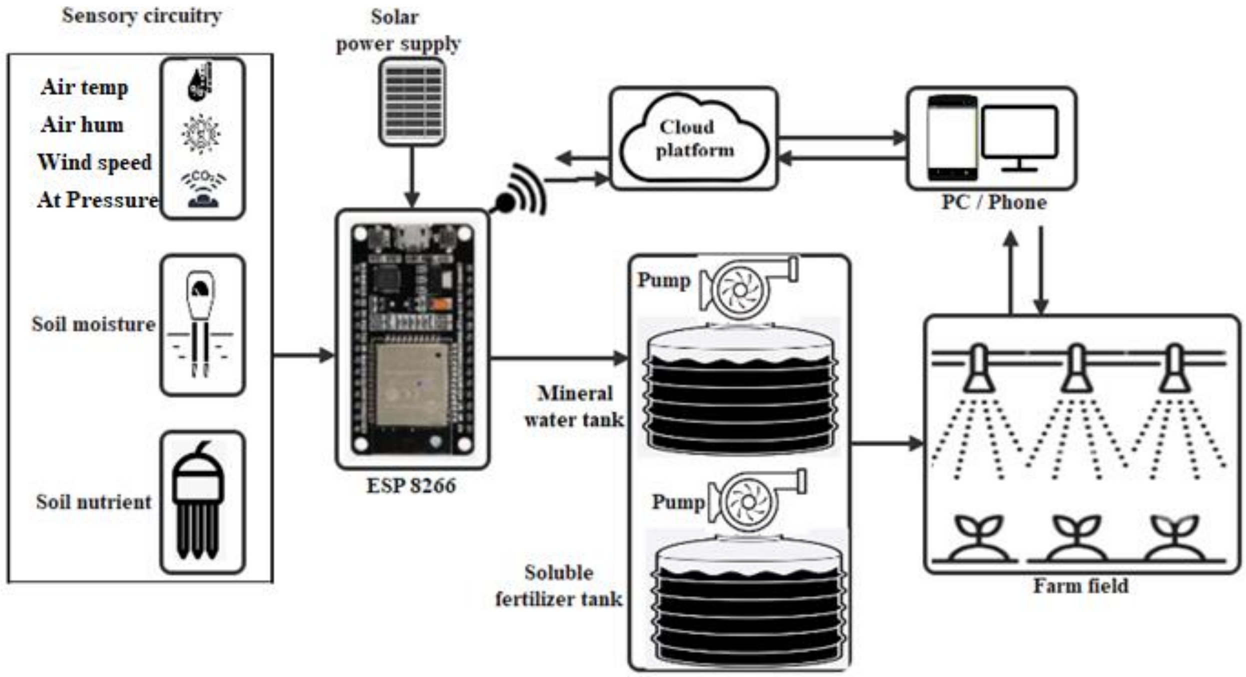

Figure 1: Architecture of the Proposed Smart Irrigation and Fertigation with Weather Prediction System

Hardware of the Embedded System

The system comprises the following key components:

i. Input sensors that are responsible for collecting the real time data from the soil including soil moisture and nutrient variations for irrigation and fertigation prediction as well as capturing real time data from environment such as air temperature, relative air humidity, wind speed and atmospheric pressure for real time weather prediction and send them to the microcontroller.

ii. Microcontroller is the heart of the embedded system. It processes the input data from different sensors and based on AI and FIS algorithms, it predicts when to irrigate or fertigate as well as activating the pumps and communication system.

iii. Actuators consist of water pumps for distributing water and fertilizers in the field according to amount needed by the plant using variable rate water pump.

iv. Finally, the communication component that includes WiFi module that is responsible for exchanging the farm field information with the farmers via smart phone.

Software of the Embedded System

Python and Tensor Flow Lite for deep learning framework were the main software tools utilized in the study for predicting water and nutrients requirements in the soil. Tensor Flow Lite allows the pre-trained model in Tensor Flow to be converted to a particular format that may be optimized for storage or processing. In addition, real data streams were collected, visualized, and analyzed using Things Speak which is an IoT analytics platform service. MatLab software was used for weather prediction as well as for simulating the Fuzzy logic system for the precision irrigation and fertigation.

Machine Learning System

ML model was developed in python and a Neuron Network Classifier based on Keras and Tensor flow was used to train the model and the training accuracy obtained was 91.7 % with only the loss of 0.22 as illustrated in the Table 1 below.

Table 1: Validation Set Confusion Matrix

Response	Irrigation	No irrigation
irrigation	96%	4%
Non irrigation	18.2%	18.8%
F1 score	0.94	0.86

Fuzzy Logic System and Matlab Tool Box Design

Fuzzy logic is a machine learning technique for intelligent decisions making to unclear problems based on the degree of truth. Fuzzy logic facilitates good decision-making because it allows for human perception and analysis based on environmental variance rather than conventional true or false judgments. MatLab Fuzzy logic toolbox was used to develop the model that uses IF-THEN rules to find the output corresponding to the crisp inputs

Fuzzy Inference System for Weather Prediction

The Fuzzy logic was applied to weather forecasting to predict the time and the quantity of the rain probable within 24 hours based on dynamic change in Air temperature, Air humidity, atmospheric pressure and wind speed.

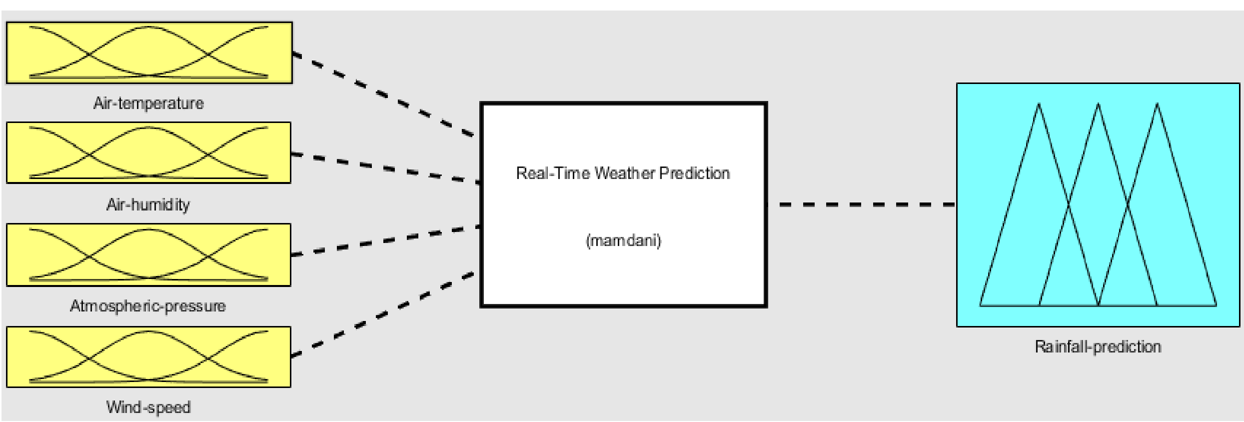

Figure 2: Fuzzy Inference System Editor for Rain Prediction

In the fuzzy inference system editor illustrated in the Figure 2, four input membership variables are presented as Air temperature, Air humidity, Atmospheric pressure and wind speed and their corresponding linguistic variables along with their corresponding ranges. The output membership function of the fuzzy inference system is the prediction of the rainfall in percentage.

Table 2: Input/Output Membership Functions and Their Linguistic Variable Ranges for Rain Prediction

Air Temp (^{0}C)		**Air humidity (%)**		**Atmospheric pressure (PPM)**		**Wind speed (km/h)**		**Rainfall prediction in %**	
Linguistic variable	**Range**	**Linguistic variable**	**Range**	**Linguistic variable**	**Range**	**Linguistic variable**	**Range**	**Linguistic variable**	**Range**
Low (L)	0-25	Low (L)	0-40	Low(L)	0-8	Low(L)	19-30	Low(L)	0-40
Normal (N)	20-25	Normal (N)	40-70	Normal(N)	8-12	Normal(N)	30-31	Normal(N)	40-70
High (H)	30-50	High (H)	80-100	Dangerous	12-20	Dangerous	31-32	Dangerous	70-100

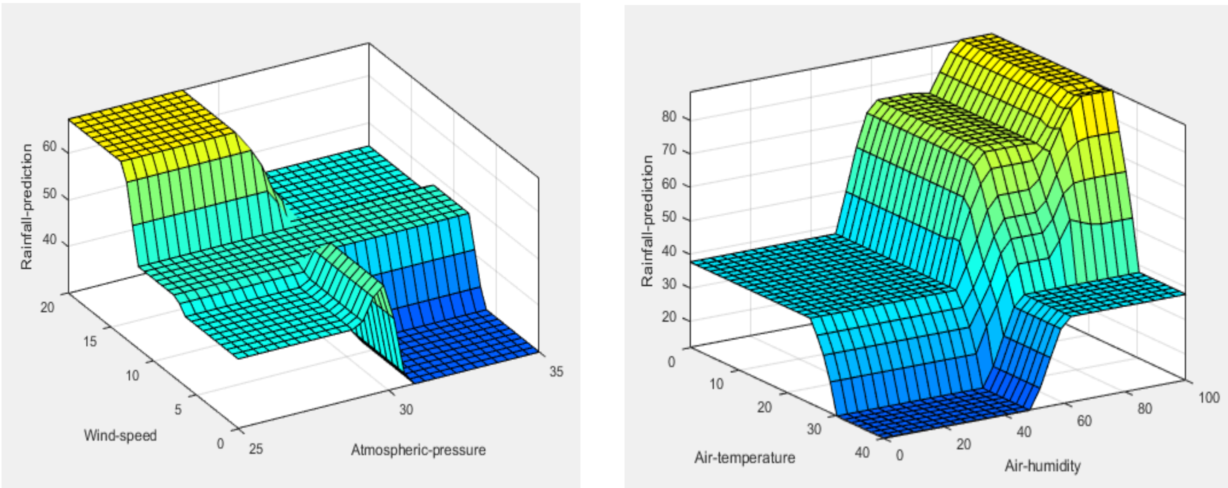

Figure 3: 3D Surface Views for the Rainfall Prediction Based on Air Temperature, Relative Humidity, Wind Speed and Atmospheric Pressure

Fuzzy Inference System for Irrigation and Fertigation

The FIS model for the system was designed with three main crisp inputs including weather pattern prediction, soil moisture and soil nutrient that are applied to the Fuzzy IF-THEN rules to provide the corresponding irrigation and fertigation outputs.

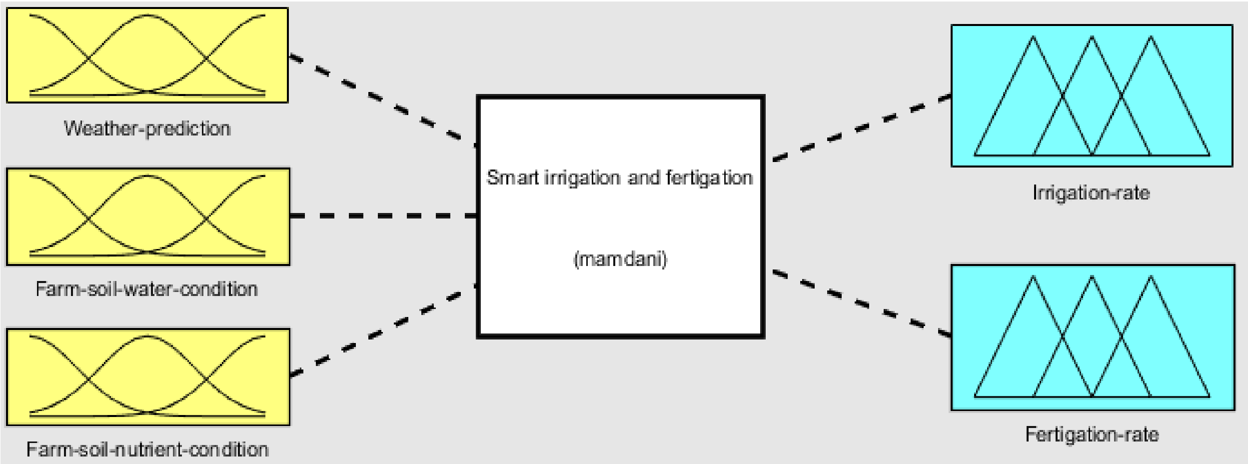

Figure 4: Fuzzy Inference System Design for Smart Irrigation and Fertigation

The estimated linguistic variables and their corresponding ranges for the inputs weather prediction, soil moisture and nutrients were used to build each of the membership functions as well as output irrigation and fertigation rates as illustrated in the Table 3.

Table 3: Input/Output Linguistic Variables and Their Corresponding Range for Irrigation and Fertigation Rates

Weather-prediction (%)		**Water-condition (%)**		**Nutrient-content (%)**		**Fertigation-rate (%)**		**Irrigation-rate (%)**	
Linguistic variable	**Range**	**Linguistic variable**	**Range**	**Linguistic variable**	**Range**	**Linguistic variable**	**Range**	**Linguistic variable**	**Range**
Very Low (VL)	0-25	Very Low (VL)	0-25	Very Low (VL)	0-25	Very Low (VL)	0-25	Very Low (VL)	0-25
Low (L)	25-50	Low (L)	25-50	Low (L)	25-50	Low (L)	25-50	Low (L)	25-50
Normal (N)	50-75	Normal (N)	50-75	Normal (N)	50-75	Normal (N)	50-75	Normal (N)	50-75
High (H)	75-100	High (H)	75-100	High (H)	75-100	High (H)	75-100	High (H)	75-100

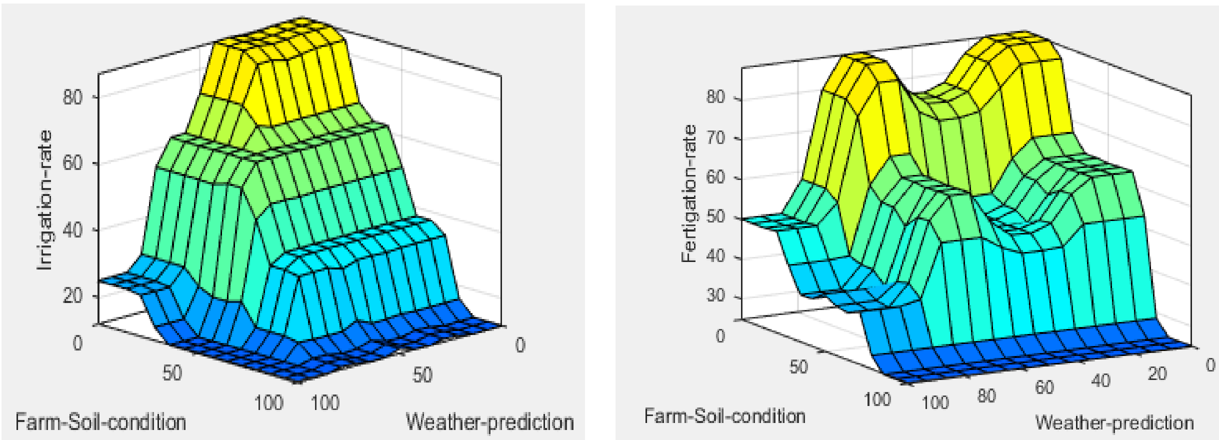

Figure 5: 3D Surface Views for the Smart Irrigation and Fertigation

Mobile Application

The mobile application was developed for farmers to interact with their farms from anywhere at any time. MIT inverter platform was used to develop a mobile application that can be installed in the farmers' smartphone. The mobile application has capabilities that allow the farmers to monitor and control the irrigation and fertigation equipment installed in the farm as well as getting all information about farm weather condition and soil condition and growing progress of the crops.

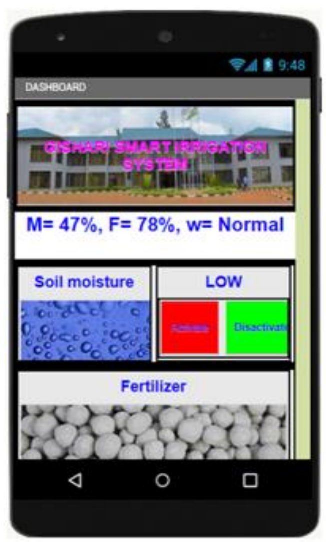

Figure 6: Mobile Application

3.0 FINDINGS

The developed system prototype was deployed in the 2 hectors Maize farm in the Eastern province of Rwanda during the second season of the year where there was varying precipitation for four months period. The system was able to predict the short-term rainfall for 24 hours period at 91.5% accuracy. Using this weather forecasting data and soil condition predicted by ML model, the irrigation and fertigation scheduling was achieved and the overall result proved that 55% of water for irrigation, 51% of energy used and 20% of fertilizers were saved as well as increases in 20% of Maize yield production compared to previous season. The developed mobile application functioned 100% and was able to indicate all weather forecasting and the variation in soil condition as determined in the farm field by the deployed prototype. In addition, the farmers were able to control and activate the irrigation and fertigation equipment properly. The results of the physical system deployed in the field corresponded to the results from Matlab simulation in Lab at 90% and the small difference was due to the law quality of sensors used and the slop of the farm land.

4.0 CONCLUSION AND RECOMMENDATION

This study presents the weather based smart irrigation and fertigation system. The proposed solution employes IoT in conjunction with AI technologies to monitor and control the irrigation and fertigation scheduling process to optimize water and fertilizer usage. It uses electronic sensors to collect real-time data and microcontrollers for processing data, actuators for activation irrigation and fertigation equipment as well as mobile application for enabling farmers to easily monitor and control their farm activities. The system prototype deployed and tested in the farm showed that the half of the water and fertilizers can be saved as well as reducing number of farm field workers when this system is well used. It is less internet dependent since all data processing are done at the edge of the network at it can be deployed anywhere even in remote area.

We recommend the implementation of this solution as it guarantee the effective usage of water and fertilizer resources which in turn increases the farmer's income. Moreover, it is less expensive and user friendly since it doesn't require special knowledge and it can be applied to any type of crops.

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