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Research Article

A microcontroller - Based Irrigation Scheduling Using FAO Penman-Monteith Equation

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ABSTRACT

This study uses the Food and Agricultural Organization (FAO) Penman-Monteith equation to develop a crop water algorithm needed to automate the supply of specific amount of water to crops, depending on their different crop water requirements. This was done to deviate from the practice of supplying the same amount of water to different crops during irrigation practices which could lead to over-irrigation or under-irrigation resulting in pest infestation and eventually low yield. The crop water requirement for cocoyam, spinach and tomatoes were estimated using data from FAO. A microcontroller-based smart irrigation device incorporated with real-time clock was developed to supply the right amount of water to crops at the right time and duration daily. The implementation was done using a laboratory-scale irrigation test bed and experimental results reveal the effectiveness of the developed system in the automation of crop-specific irrigation systems and in line with their Crop Water Requirement (CWR). Possible applications include greenhouses where researchers have to apply a specific amount of water to crops for experiments; horticultural gardens and nurseries to mention a few.

Keywords: *Irrigation, Crop water use, Automation, Scheduling, Penman-monteith*

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INTRODUCTION

An automated irrigation is a system of operation with no or just a minimum of manual intervention apart from the surveillance. All systems of irrigation viz drip, sprinkler, and the surface can be automated with the help of timers, sensors or computers, or mechanical appliances (Yogesh *et al.*, 2016; Kamienski *et al.*, 2019). In recent time, there seems to be a paradigm shift from traditional irrigation practices to smart irrigation. This means that certain algorithms are programmed into microcontrollers, making use of sensors, real-time weather, and site data in order to achieve a "smart" and properly scheduled irrigation system (Omid *et al.*, 2020; Zia *et al.*, 2021). These smart controllers sometimes make use of weather or site data to determine when irrigation scheduling will take place for maximum crop production. Some of them also make use of soil conditions, evaporation and crop water use to automatically operate a scheduled irrigation system to meet the needs of a variety of crops.

Agriculture plays very vital role in the economic development of a nation like Nigeria. A good agricultural practice is depended on environmental parameters such as soil moisture, temperature, humidity, pH, and solar radiation (Yogesh *et al.*, 2016). This plays an important role in overall development of the crop and good yield especially as these parameters determined when to irrigate a farm. Successful irrigation practice in any location is very crucial to irrigation scheduling. A smart irrigation system uses information from environment to control when and where irrigation is required (Kizito *et al.*, 2016). The system helps in avoiding wastage of water or energy and low-crop yield, respectively. Water is a critical resource in agriculture, and supplying the right amount is essential for healthy plants and optimum productivity. Rightful application of water to a crop is very important especially during drought (Ewemoje *et al.*, 2018).

Lately, there is rapid growth of research into smart irrigation. The main reasons for this are to increase the crop yield and minimizing human labor. Wastage of water and money spent on labor is avoided in automated irrigation (Sandeep and Deepali, 2017). Also, there is tremendous increase in the rate of adoption of smart technology in agriculture by the developing nations of the world. This has made the market in Asia Pacific to witness a significant intensification in smart agriculture. Countries such as Australia, China, India, Japan, and South Korea are witnessing an extensive growth in the market (Kizito *et al.*, 2016).

However, several works have been done in smart irrigation. For example, (Wardlaw and Bhaktikul, 2004) developed a genetic algorithm for irrigation scheduling with the objective of achieving equity in water delivery throughout the season among the multiple outlets from an irrigation canal system (Torres-Sanchez *et al.*, 2020; Raeth, 2020).

Dorji *et al.* (2017) developed an irrigation scheduling and water requirement-based irrigation system for Citrus Mandarin using tensiometers. This system combines the Food and Agricultural Organization (FAO) Pan Evaporation method and Food and Agricultural Organization (FAO) Penman-Monteith equation in determining the crop water requirement of the plant. The moisture stress readings are obtained at different depths using tensiometers. The project developed a citrus water requirement scheduling irrigation system.

In Agugo *et al.* (2009), the authors designed and implemented a theoretical estimate of crop evapotranspiration and irrigation water requirements of Mungbean (*Vigna radiata*) in a low land rain forest location of southeastern Nigeria. The estimation of crops was done in three stages – the calculation of reference crop evapotranspiration, crop coefficient and the maximum evapotranspiration (Omid *et al.*, 2020).

Rodriguez *et al.* (2015) developed an automatic irrigation scheduling soilless culture system using a new control algorithm. This system uses a Proportional Integral Derivative (PID) controller and an irrigation control tray with two electrodes (level sensor). Crop water consumption was determined by the process of evapotranspiration. The PID-based irrigation control simulation model included a crop simulation model to estimate the water acceptance of the crop over a given period, water equilibrium in the tray to calculate the drainage water volume and resulting leaching fraction and a PID controller to calculate the dimension intervals between two irrigation events.

In an attempt to judiciously manage the use of water in irrigation practices, the authors in Ogidan *et al.* (2019) developed a smart irrigation system with water management capability. The system prioritizes water used for irrigation based on the amount of water available in the reservoir measured by an ultrasonic sensor positioned on the lid of the reservoir. With this type of information about available water, the system was able to determine the number of pumps to be deployed for water supply to the different farms at a particular time (Ogidan *et al.*, 2019).

However, it has been estimated that 40% of the fresh water used for agriculture in developing countries is lost, either by evaporation, water spills, or absorption by the deeper layers of the soil, beyond the reach of plants roots (Munoth, 2016). This is the reason a drip irrigation system that supplied water directly to the root of crops is more preferred to the sprinkler type of irrigation system when it comes to water management. Another way of ensuring efficient water management in irrigation practice is to ensure that only the exact amount of water required by a particular plant is delivered to it, no more, no less. In order to achieve this, the required water for each crop from planting to maturity must be known. This is what is referred to as crop water requirement (CWR) and the CWR is different from one crop to another.

Many of the automated irrigation systems developed are found to deliver water to crops on a generic basis without taking into consideration their individual water requirements (Wardlaw and Bhaktikul, 2004; Ogidan and Afia, 2019; Ogidan *et al.*, 2019). This means that they deliver the same amount of water to different crops. In reality, all crops do not require the same amount of water for their growth if they would deliver maximum yield. For instance, tomatoes and yam do not require the same amount of water for their growth. Some researchers who have taken time to estimate the crop water use of various types of crops did not implement automation of their watering schedules (Yadav *et al.*, 2018; Agugo *et al.*, 2009; Surendran *et al.*, 2017; Dorji *et al.*, 2017; Raeth, 2020). Manual (unautomated) watering is cumbersome, laborious, and ineffective because the farmer or researcher can forget to wet the crops at the required time. This challenge therefore necessitates the need to develop an irrigation system that is crop specific. The system delivers the right amount of water to different crops based on the specific crop water requirement of each crop and execute an automation system for the irrigation scheduling.

MATERIALS and METHODS

The approach adopted in this work is divided into three namely: determination of the daily water needs of the crops, determination of irrigation duration for each day and development of a microcontroller-based irrigation scheduling device.

Determination of the Daily Water Needs of the Crops

The CWR or evapotranspiration rate (mm) is the water needed to meet the water consumption through evapotranspiration (ETc) for crops to thrive and to achieve full yield potential under the given growing environment (Brouwer and Heibloem, 1986). The evapotranspiration rate is the amount of water that is lost to the atmosphere per time through the leaves of the plant, as well as the soil surface.

ET_c data used in estimating the CWR in this research is calculated by using the modified Penman–Monteith equation recommended (Brouwer and Heibloem, 1986; Yadav *et al.*, 2018; Surendran *et al.*, 2017; Omid *et al.*, 2020).

$$ET_c = \mathrm{ET_o} \times \mathrm{K_c} \tag{1}$$

where: ET_c refers to crop evapotranspiration or crop water need (mm/day); ET_o – is the reference evapotranspiration (mm/day); K_c – indicates Crop Coefficient Factor.

Determination of ET_o

Reference evapotranspiration (ET_o) represents the influence of the climate on crop water needs and it is usually expressed in millimeters per unit of time, e.g. mm/day, mm/month, or mm/season. Grass has been taken as the reference crop (Brouwer and Heibloem, 1986).

In this research, a more simplified version of the Penman-Monteith equation is used in the estimation of ET_o as shown in Equation 2.

$$ET_o = \frac{0.408\Delta(\mathrm{R_n} - \mathrm{G}) + \gamma\frac{900}{\mathrm{T}+273}\mathrm{u_2}(\mathrm{e_s} - \mathrm{e_a})}{\Delta + \gamma(1 + 0.34\,\mathrm{u_2})} \tag{2}$$

where: ET_o – refers to reference evapotranspiration, mm day^{-1}; R_n - is the net radiation at the crop surface, MJ m^{-2} d^{-1}; G - indicates soil heat flux density, MJ m^{-2} d^{-1}; T – is the mean daily air temperature at 2 m height, °C; $\mathrm{u_2}$ – is the wind speed at 2 m height, m/s; e_s - is saturation vapor pressure, kPa; e_a is the actual vapor pressure, kPa; $e_s - e_a$ - indicates saturation vapor pressure deficit, kPa; Δ - is the slope of saturation vapor pressure curve, kPa °C^{-1}; γ - is psychometric constant, kPa °C^{-1}.

Determination of Coefficient Factor, K_c

The crop coefficient is a mathematical conversion factor that relates and converts the ET of the reference crop to the crop of interest (actual crop water use). The magnitude of the crop coefficient $\mathrm{K_c}$ is not constant all through the season. It varies depending on the growth stage and the relative maturity of the crop as well as some management practices.

Table 1 shows per crop the K_c values for different growth stages as well as the average K_c for the total growth period of each of the crops considered in this research namely cocoyam, spinach, and tomatoes.

In order to calculate the Crop Evapotranspiration (ET_c) or Crop Water Requirement of various crops under study, the reference evapotranspiration (ET_o) is multiplied with the crop coefficient (K_c) as illustrated in Equation 1.

Based on equation 1, the estimated crop water requirements (ET_c) of different crops under study from planting to maturity is shown in Table 2 (Brouwer and Heibloem, 1986).

Table 1. *Crop specific coefficients (K_c) per crop development stages for various crops under study.*

Crop	Initial stage (K_c)	Days	Crop dev. stage (K_c)	Days	Mid-season stage (K_c)	Days	Late season stage (K_c)	Days	Season average (K_c)
Cocoyam	0.45	-30	0.85	-40	1.35	-95	0.95	-35	0.9
Spinach	0.45	-20	0.6	-30	1	-40	0.9	-10	0.74
Tomato	0.45	-30	0.75	-45	1.15	-70	0.8	-30	0.79

Table 2. *Estimated crop water needs of different crops from planting to maturity (Agugo et al., 2009).*

Crop	Crop water needs (mm/total growing period)	Average water needs (mm/total growing period)	Total growing period (days)	Average growing period (days)
Cocoyam	600-900	750	200 – 240	220
Spinach	350 – 500	425	60 – 100	80
Tomatoes	400 – 800	600	135 -180	158

From Table 2, it is possible to estimate the daily water needs by dividing the average crop water needs for the total growing period by the average gestation period (number of days from planting to maturity). The result shows 3.40 mm day^{-1} for cocoyam, 5.31 mm day^{-1} for spinach and 3.79 mm/day for tomatoes as shown in Table 2. This means that this is the estimated amount of water needed daily by these crops for maximum yield. Meaning the supply of water more that those specified in table 2 or less than that on a daily basis could adversely affect the yield resulting in low yield.

Determination of the Duration of Irrigation Per Day

In this work, an automated irrigation scheduling approach is adopted using microcontroller technology. To develop the automated system, certain hardwares were used including Arduino UNO, 1-Channel relay module, soil moisture content sensor, water reservoir, DHT11 sensor, Liquid Crystal Display (LCD), Real-Time Clock (RTC) module. The software used include Arduino sketch. The block diagram of the developed system is shown in Figure 1. The system is divided to three main parts which are the data acquisition, processing, and the system output.

Data Acquisition

This includes the Digital Humidity and Temperature (DHT) sensor and the moisture content sensors. The DHT measures the environmental temperature and humidity while the moisture content sensors are in form of probes, and they are buried in the (farm) soil to acquire the moisture content of the different farm soils in order to determine if the soil samples have enough moisture (indicating wetness) or it does not (indicating dryness). The sensor readings are fed into the microcontroller for further processing as illustrated in Figure 1.

Processing

The processing is that part of the system that takes decision about how the device should operate based on the acquired sensor readings and the threshold values at which the system should take decisions. The microcontroller used is an Atmeg 328 microcontroller housed in an Arduino Uno board. Interfaced with the microcontroller is a real-time clock (RTC) module. The work of the real-time clock is to assist in keeping track of time (seconds, minutes, hours, days, months, and years) in an accurate manner. RTC can do this for almost a decade. It is a choice component for clocks, calendars, or any other time-keeping project. Here, it is used to keep track of the time (seconds, minutes, hours) the systems are expected to supply water to crops in line with watering schedule. A program of the crop watering schedule is written in the Arduino Integrated Development Environment (IDE) and uploaded into the microcontroller for execution. The schematic circuit of the developed system is shown in Figure 2 while the flowchart of the program is shown in Figure 2. Each of the three moisture content sensors are made to represent different locations in the farm namely cocoyam farm, spinach farm and tomatoes farm. If the moisture content indicates the soil is dry in any of the three farm locations, the system activates the appropriate pump to release water to crops in that location. The specific time irrigation commences is specified by the RTC for example, if the RTC specifies 6:10:05 am, this means 6th hour, 10th minute and 5th second. The system ensures that the water is supplied at this specific time on a daily basis throughout the period of planting. If the moisture content reading indicates a wet soil, the system does not initiate water supply because there is no need for irrigation. The soil moisture content sensor used in this work is the Arduino compatible type shown in Figure 6. Three sensors were used and connected to analog pins A0, A1 and A2 of the Arduino Uno microcontroller board as part of the smart irrigation test bed developed in the Department of Electrical and Electronics Engineering in Elizade University (Ogidan et *al.*, 2019). The purpose of developing this irrigation test-bed is to act as a generalized platform to assist researchers and students in the testing of different algorithms they develop in the field of smart irrigation system. The soil moisture sensors were calibrated with standard digital soil moisture sensor and to give measured moisture values in percentage. If the sensor value falls within 2% to 39%, this indicates that the soil is dry. If the sensor value falls within 40% to 99%, this indicates that the soil is wet. If the moisture content sensor values indicates that the soil is wet, then there is no need for irrigation.

System Output

The system output comprises of the actuators including relays and pumps, which are used to supply water to the farm site, Liquid Crystal Display (LCD) for display of the system activities for the viewing the system operation. All these are concerned with how the decision of the microcontroller is deployed and made visible to the user. Figure 3 shows the various components of the control unit being coupled, while Figure 4 is the control unit after coupling.

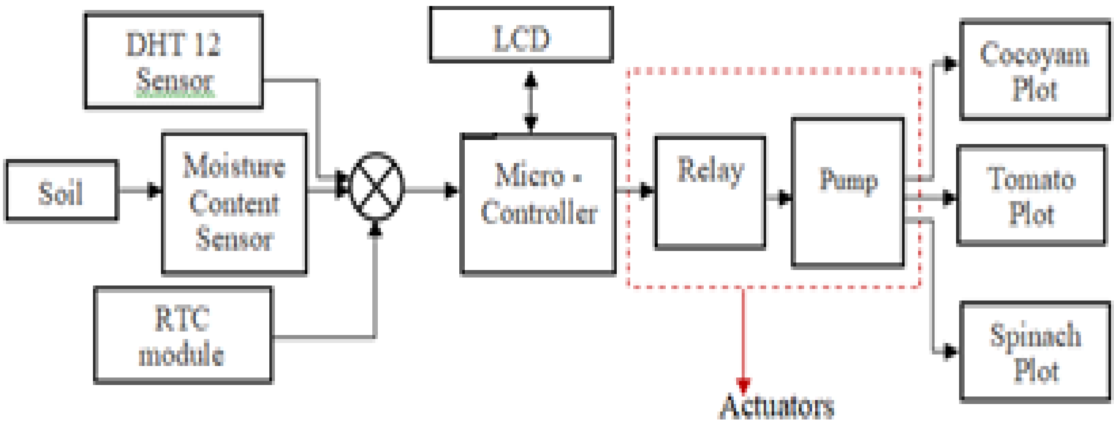

Figure 1. *Block diagram of the smart irrigation system based on crop water use.*

Testing

For the purpose of testing the developed device, it was connected to the laboratory-scale irrigation test bed as shown in Figure 5. The irrigation test-bed depicts a farm setting with irrigation facilities such as reservoir, pumps, sprinklers, farm sites and so on used for testing irrigation systems in a laboratory setting (Ogidan et *al.*, 2019). The system was set up using three moisture content probes and three soil samples were provided in containers representing soils of different farms (cocoyam, spinach, and tomatoes) soils. The probes were dipped into the soil samples one after the other.

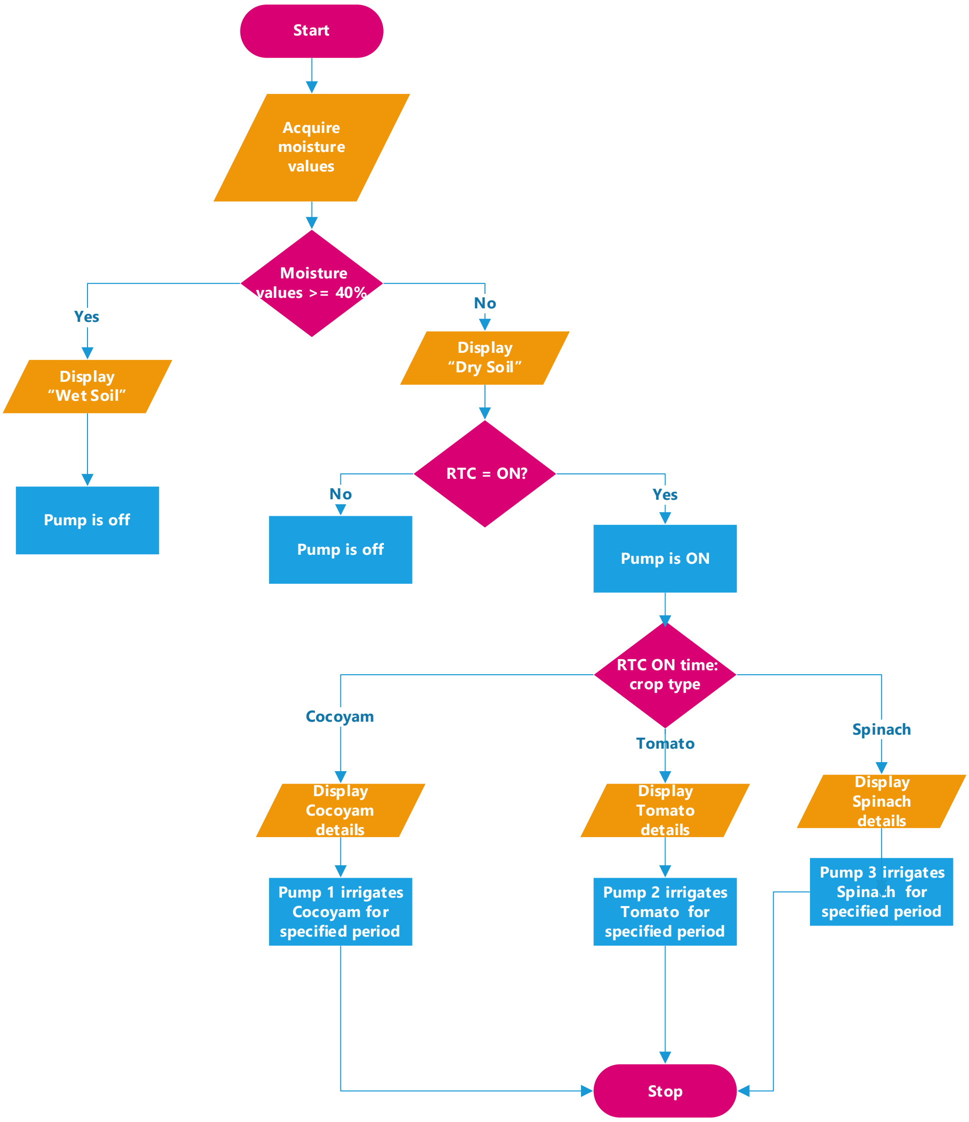

Figure 2. Flowchart of the smart irrigation system based on crop water use.

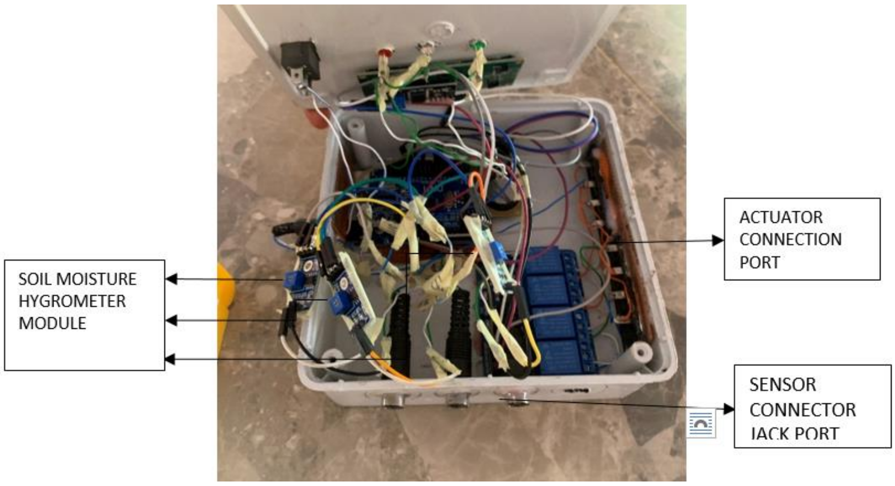

Figure 3. System being coupled.

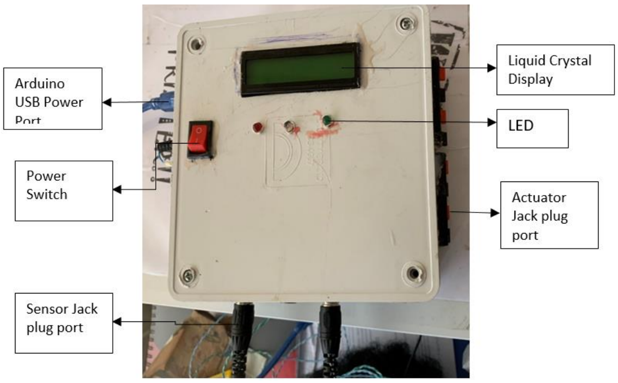

Figure 4. *Developed system after coupling.*

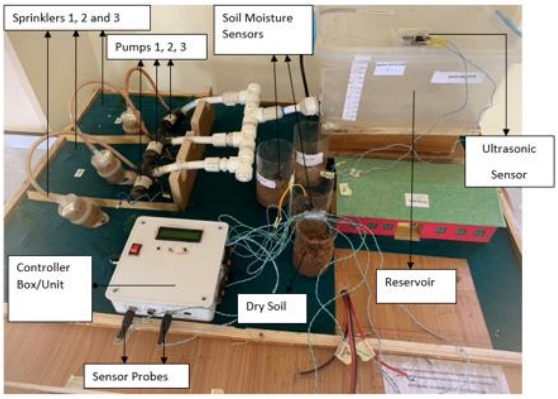

Figure 5. *Laboratory-scale smart irrigation test-bed (Ogidan et al., 2019).*

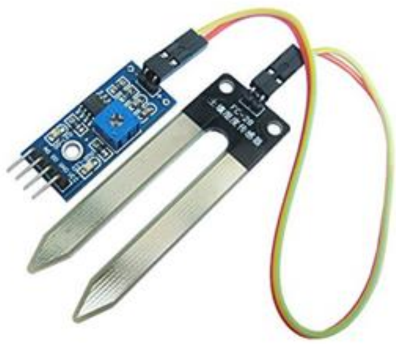

Figure 6. *Soil moisture sensor.*

RESULTS AND DISCUSSION

Table 5 shows the results for the effect of the moisture content sensors and the real-time clock (RTC) on the pumps connected for each farm Cocoyam, Tomato, and Spinach respectively. With the moisture content sensor dipped in samples of dry soil, irrigation process was initiated in each of the farms, but the water was not supplied until the exact time specified by the RTC is reached. For instance, in case of cocoyam with a soi moisture of 15%, even though the LCD indicates that the soil is dry, water was not supplied to the cocoyam farm until 7:15:13 a.m. When it was 7:16:25 am exactly, the irrigation pump was turned off in line with the time set in the RTC. The watering commenced at 7:15:13 am and stopped at 7:16:50 am daily after supplying water for 97 seconds. The only time the irrigation process was not activated was when the soil was wet (between 84% and 99%) meaning there was no need for irrigation. The same goes for spinach with 13% soil moisture indicating dry soil that commenced irrigation at 7:45:13 am and stopped water supply at 7:47:01 am after 108 seconds. In the case of tomatoes with moisture content of 20% indicating dry soil, the daily irrigation commenced at 7:30:13 am and stopped at 7:32:44 am after a duration of 151 seconds.

Table 5. *Irrigation schedule for the three crops based on the RTC.*

Soil Moisture (%)	Crop Type	RTC irrigation 'ON' time (hh:mm:ss)	RTC irrigation 'OFF' time (hh:mm:ss)	Irrigation duration per day (s)
15	Cocoyam	7:15:13	7:16:50	97.13
20	Tomato	7:30:13	7:32:44	151.70
13	Spinach	7:45:13	7:47:01	108.28

CONCLUSION

In this work, a crop-specific crop water requirement algorithm based on data obtained from FAO Penman-Monteith equation was developed and emulated using a laboratory-scale irrigation testbed. RTC was employed in executing the irrigation scheduling by ensuring that the required amount of water was delivered as at when due on a daily basis without human intervention. The system helps to minimise water usage in that the required amount is delivered to the root of crops thus preventing over-irrigation or under-irrigation. Future work would involve implementation of the developed algorithm on a pilot farm and the incorporation of mini-weather station to provide online weather parameters for real-time computation of crop water requirements for different crops.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no conflict of interest.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Olugbenga Kayode Ogidan designed the concept of entire project. The investigation, methodology and writing of the original draft were done by him, read and approved the final manuscript.

Samuel Dare Oluwagbayide was involved in the methodology and former analysis of the experiment. He carried out the review and editing of the original drafted copy, read and approved the final manuscript.

Thomas Olabode Ale participated in the designed and investigation of the experiment. He also handled the data curative and validation, read and approved the final manuscript.

ETHICS COMMITTEE DECISION

This article does not require any ethical committee decision.

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