ORIGINAL RESEARCH ARTICLE

Development of an IoT-based automatic fertigation system

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ABSTRACT

Fertigation supplies water and liquid fertilizer through the same channel to plants. Using drip irrigation set up for fertigation allows the root zone of the plant to be continuously supplied with nutrients and water throughout the farm season. Conventionally, fertigated systems are controlled using pre-set timers to turn on and off fertilizer injectors and irrigation pumps, and also to set the frequency and duration of supply. Therefore, fertigation management is usually based only on predictive algorithms or historical data, which may not be accurate for all situations.

Development of a microcontroller-based fertigation management system within the Nigerian (Sub-Saharan Africa) region using a capacitive soil moisture sensor and a JXCT-IOT Frequency Domain Reflectometry (FDR) soil nitrogen sensor is presented. The sensors are placed in the soil around the root region of plants to enable a microcontroller to monitor the soil properties, determine how much water or nutrients the plant needs, and supply the amount needed through a drip irrigation framework. The tap water and urea solution are placed inside separate reservoirs and supplied to the plant through solenoid valves controlled by the microcontroller. Furthermore, an Internet of Things (IoT) client (Blynk IoT) was integrated with the fertigation system so that the fertigation process, as well as the soil state, could be monitored and controlled remotely. The data read from the sensors as well as the state of the solenoid valves were sent over the internet to be stored on the Blynk servers. A website and mobile (Android) dashboards were also created using the Blynk IOT platform to display the states of the valves and the sensor readings.

The automatic fertigation system was found to be functional. The system keeps the soil moisture and nitrogen content between the recommended ranges: moisture content between 25% and 46% and nitrogen content between 20 mg/kg and 30 mg/kg for cucumber crops. Fertigation events occur every morning between 5 and 6 am.

Keywords: Precision agriculture, fertigation, drip Irrigation, sensors, internet of things

1.0 Introduction

In recent years, there has been a myriad of research into Precision Agriculture (PA). This is because it allows for the management of small-to very large-scale crop production while using

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fewer traditional inputs (land, fertilizers, pesticides, water, and herbicides). PA promotes the efficient use of farm input resources, enables sustainable production, prevents soil degradation, and reduces the cost of production while having improved yields.

Efforts have been made to increase the efficiency of irrigation and fertilizer application. The two processes can be combined into a single one called fertigation. This is defined as the application of fertilizer solution with irrigation water, often regularly, in small quantities. Fertigation is more advantageous than the broadcast application of fertilizer because it allows uniform application over a wide area. There is less variation in the soil nutrient concentration, the crop's use of nutrients is more efficient, and there can be a more precise application of nutrients according to the plant's needs. Fertigation is usually applied through drip irrigation or micro-sprinklers. Recent applications for fertigation have been in hydroponic systems and fertilizer applications in sandy soils, which have low nutrient retention.

Fertilizer application rates can be adjusted weekly based on the nutrient requirements. However, the fertigation events should be frequent to maintain a moderate soil water content. If the soil water content is low, nutrients will be concentrated on the top layer of the soil and will not be able to be absorbed by plant roots.

A prolonged lack of water in the soil often leads to crop failure (Wamugunda *et al.*, 2019). Excessive water can also harm certain crops (Gitonga et al., 2019).The field capacity (FC) of the soil is the amount of water in the soil when all excess water is allowed to drain freely after the soil has been saturated. This usually takes about 2-3 days after saturation and is the point at which water drainage/deep percolation due to gravitational forces has stopped. The (Permanent) Wilting Point (PWP), on the other hand, is the soil water content when water cannot be drawn from the soil using the roots of the plant, and the plant begins to wilt and die, and even fails to recover its turgidity when water is added. Therefore, the amount of water available to the plants is the amount between the field capacity and the permanent wilting point. This amount is also called the Total Available Capacity.

When designing or operating an irrigation system, the amount of water in the soil should not be allowed to approach the permanent wilting point consistently, as this will not be optimal for the plants being cultivated. The plants will be constantly stressed and therefore will have much lower yields than possible. To combat this, we define a term called "Readily Available Water" (RAW), which is usually pegged as the lower limit for the soil water content when managing an irrigation system. It is the amount of water available in the soil that can be easily extracted by the plant. It can be calculated as in Eq. 1.

$$\boldsymbol{RAW = (FC - PWP) \times RZ \times MAD} \qquad \textbf{(1)}$$

Where PWP is the permanent wilting point of the soil, dependent on the soil texture; RZ is the root zone of the plant; MAD is the maximum allowable depletion which depends on the plant being considered.

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When managing the amount of nutrients in the soil (in this case, nitrogen and nitrate-ion), nutrient supply within the soil should be kept within a certain optimal range to maintain healthy crops. This range is dependent on the kind of crop being planted. For instance, Wang *et al. (*2018) reported that the cucumber yield was of maximum quality only when the supply of irrigation water and nitrogen were within a certain range of values (124–151 mm and 318–504 kg/ha, respectively). Therefore, there has to be a commitment in fertigation management to neither over-fertigate nor under-fertigate. This point is illustrated in Figure 1.

Drip irrigation, also known as trickle irrigation, has water supplied to plants through perforated pipes or special outlets called emitters placed just below the soil surface or just above it. It supplies water slowly in drips to the roots and stems. Multiple outlets can be created and directed to supply only the plants that need it. Drip irrigation systems are preferred because they make it easy for the soil properties to be maintained consistently at an optimal range, reducing plant stress and increasing yield. Water-soluble fertilizers can also be injected into the system at the control head and supplied together with the irrigation water. Drip irrigation systems result in reduced water losses through deep percolation, surface runoff, evaporation, and increased water-use efficiency.

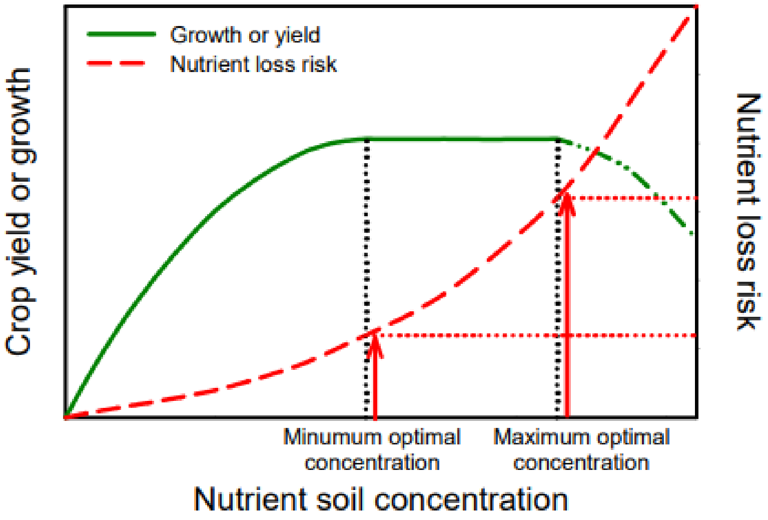

Figure 1: Graph showing the relationship between soil concentration, crop yield, and nutrient loss risk (Fuglie, 2016).

For optimizing the management of irrigation and N supply, there are 2 suggested techniques: prescriptive management and corrective management. Prescriptive management involves determining the application rate before planting based on the expected crop demand, the quantity of nitrogen (N) and water supplied from local sources, nitrogen and water use efficiency, and the climate. Using this method, the target nitrogen and water availability will be the amount of nitrogen and water taken up by the plant within that period. Corrective management, however, uses tools to determine plant status during the growing season and data gotten from the tools as the basis of making Fertigation management decisions at

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different growth stages. Tools used for corrective management include near-infrared leaf N analysis, chlorophyll meters, leaf colour charts, soil reflectance sensors, EC probe sensors, and soil nutrient probe sensors. Using this approach, the amount of fertilizer and water supplied is varied regularly based on the measurements to prevent excess supply or deficiency (Giller *et al.*, 2004).

Soil and crop properties can be measured using a variety of sensors. These measurements can be used to adjust the rate and amount of fertigation. The Capacitive Soil Moisture Sensor measures soil water content by determining the dielectric permittivity of the soil. Capacitive soil moisture sensors have two probes which serve as the plates of the capacitor, and the soil serves as the dielectric between them. They have a high-frequency oscillator that drives the capacitor. When this oscillating voltage is applied to the capacitor, the output gain will be proportional to the soil's relative permittivity. The working of the moisture sensor is shown in Figure 2.

The capacitive soil moisture sensor output depends on the complex relative permittivity of the soil. The sensor does not directly measure the dielectric permittivity, but the sensor output can be related to the Volumetric Moisture Content (VMC). It has been shown that the sensors can predict VMC with an accuracy of about 3.5–6% (Adla *et al.*, 2020).

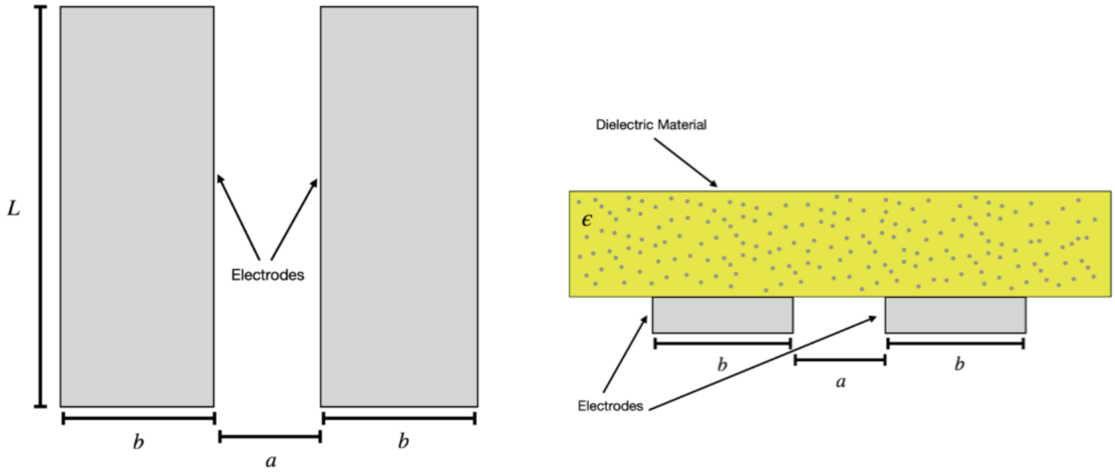

Figure 2: Working of capacitive soil moisture sensor (Hrisko, 2020).

Soil Nitrogen FDR Sensors usually consist of three probes or waveguides, which are connected by a coaxial cable. The middle probe is connected to the core of the coaxial cable while the other ones are connected to ground shielding. The sensor essentially acts as a three-prong coaxial sensor.

When an alternating signal is generated by an oscillator in the sensor head, the electromagnetic wave is transmitted via planar waveguides (probes). This generates an alternating electrical field which is applied to the soil. Using the probes, we can measure the

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complex dielectric permittivity of the soil. This permittivity is dependent on the frequency of the alternating signal, as seen in Equation 2.

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}' - \mathbf{j}\left(\boldsymbol{\varepsilon}''_{rel} + \frac{\boldsymbol{\sigma}}{2\pi f \boldsymbol{\varepsilon}_0}\right) \qquad (2)$$

where ε *is the complex dielectric permittivity,* ε' *is the real part of the permittivity that measures the polarization of the soil,* ε''_{rel} *is a relaxation component of the imaginary part of the permittivity,* σ *is the bulk conductivity, usually approximated by direct current conductivity), and* ε_0 *is the permittivity for free space (8.854 ×* 10^{-12} *F* m^{-1}*).*

The real part of permittivity is related to the water content of the soil, while the imaginary part of permittivity is related to electrical conductivity and dielectric relaxation. At low operating frequencies, the effect of conductivity has a higher effect on the apparent permittivity than the capacitance. However, above 100 MHz, the conductance has a negligible effect on the apparent permittivity and the value of apparent permittivity can be taken as solely dependent on the relaxation of the ions being measured (Skierucha and Wilczek, 2010).

Each ion has a characteristic frequency, which is the frequency at which it resonates, and it is inversely proportional to the ion's size. Based on the Debye-Falkenhagen theory, to measure the concentration of a particular ion, if the period of the electromagnetic oscillation applied to the medium is much smaller than the relaxation frequency, the ionic atmosphere will be in an asymmetric state. However, when the period of the alternating field is close to the value of the relaxation time of an ion, the ionic oscillations will be so fast that net ionic motion in a direction will be smaller, making the ionic atmosphere less asymmetric. The ionic symmetry affects the relaxation component of the imaginary part of the permittivity, and this is what causes the sensor to be sensitive to particular ions. The value of relaxation time in nitrate salt solutions has been determined to be a minimum of 1.9ps. Therefore, the Debye-Falkenhagen effect in a nitrate salt solution occurs at a frequency of about 500 MHz for low concentrations. (Adachi *et al.*, 1998).

1.1 Related works: IoT in fertigation

The Internet of Things (IoT), in basic terms, can be defined as the interconnection of devices (physical and virtual) that have sensors, processing capability, and software within a network (such as the internet) to enable intelligent decision making. Within the context of agriculture, smart farming is becoming the norm and there has been wide adoption of agricultural drones and sensors. These can create maps of the farmland, indicating the level of variables such as temperature, pH, nutrient concentration, and water concentration. The maps can be used to schedule and control irrigation, fertilizer, and pesticide applications, among other farm processes, to a high degree of accuracy. Self-driving tractors are being manufactured that can automate these processes. Business Insider predicts that there will be around 12 million agricultural sensors in use across the world by 2023 (Meola, 2021). These IoT devices also generate a lot of data points that can be utilized in predictive AI models.

Farming using IoT technologies is slowly becoming the norm because it aids precision agriculture. It reduces farm costs such as labour and it increases the efficient use of farm inputs because the use of chemicals such as pesticides and fertilizers is reduced to only the accurate amount needed by the plants. IoT systems also enable the farmer to make quick decisions and react to issues arising on the farm, such as crop health and weather conditions. The inclusion of IoT systems in farming will generally lead to a better quantity and quality of farm produce.

IoT systems have been proposed and implemented to control fertigated farmlands. (Raut *et al.*, 2018) implemented a system that detected soil moisture levels using a moisture sensor and nutrient deficiency using a colour sensor. The required amounts of nitrogen, potassium, and phosphorus were added to a water tank. The solution was supplied to the soil if the soil moisture sensor reading was below a certain value and the whole operation was reported via email. The system, however, could not have given accurate soil measurements because the colour of the soil is not an accurate indication of the level of particular nutrients within the soil.

Abidin and Ibrahim (2015) designed a web-based automatic fertigation system using the Zig-Bee framework. The design included soil moisture, environmental temperature, and humidity sensors. It utilized a SQLite database with a Lighttpd web server. It was implemented as an effective way for farmers to control and monitor the state of their farms over the internet, regardless of their location.

While the above solutions combine sensors and control modules into a single node, Ahmed, Osman, and Awadalkarim (2018) described a solution involving multiple sensor nodes on farmland, with each node covering a certain area. Each sensor node sends data to the main node through the XBee protocol. The main node is connected to the internet and allows real-time monitoring of the farmland state. The system was seen to work well over a coverage area of 1.5 square kilometers.

This research work seeks to test and implement a single-node automated fertigation system using capacitive soil moisture sensors and a novel low-cost soil nitrogen meter, allowing it to automate the irrigated water and nitrogen fertilizer supply and frequency through a drip irrigation system. It utilizes web and mobile dashboards to display the system status.

2.0 Research methodology

There are two basic parts to this proposed system: the automatic fertilization system and the IoT platform. The Fertigation system works autonomously and controls the supply of water and liquid fertilizer based on the sensor values. It sends the fertigation state and sensor values to the IoT server. The IoT (in this case, the Blynk IoT platform) stores the data on its servers and displays the fertigation state and sensor values using the web and mobile dashboards. It also enables an override of the fertigation system's functionality by sending control commands to the fertigation system. The data flow of the system is illustrated in Figure 3.

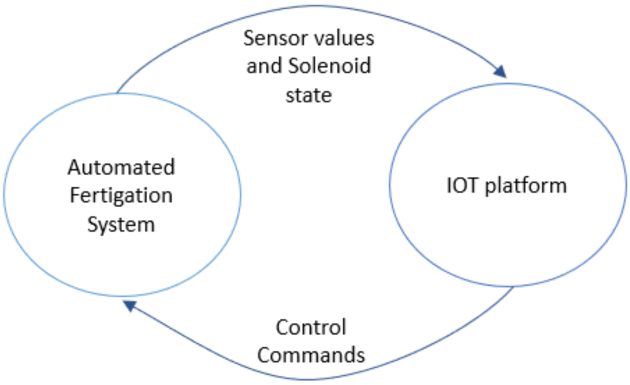

Figure 3: Data flow diagram of the implemented system

2.1 The automatic fertigation system

Automatic fertigation controls the fertigation of the plant. It is, in essence, a drip irrigation system that has had a fertilizer solution injected into it. Figure 4 shows the general block diagram of the system.

This consists of the four sub-systems. The first sub-system is the drip irrigation system, comprising the water and fertilizer storage tanks, PVC pipes, low-density polythene (LDPE), the drip irrigation lateral tube, a ½ gallon per hour drip irrigation emitter, and a 12V plastic solenoid valve. The Remote Control and Monitoring Unit is the second sub-system. The Capacitive soil moisture sensor V2.0 and the JXCT-IOT Soil Nitrogen (Nitrate) sensor (0–5V) are the third and fourth sub-systems, respectively.

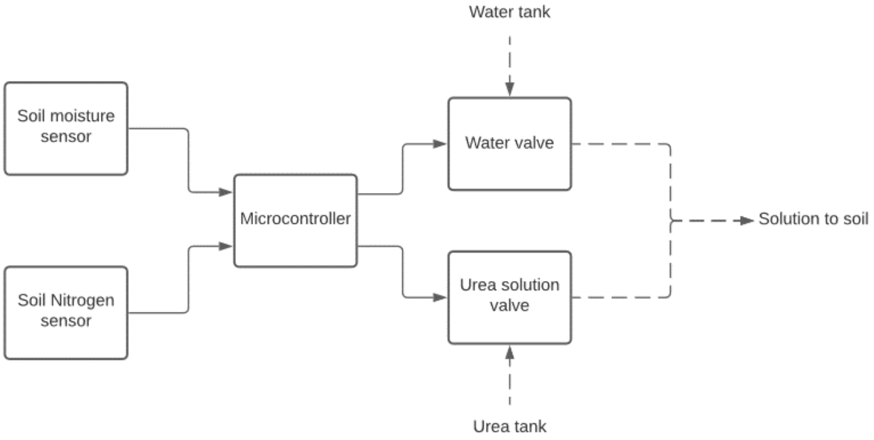

Figure 4: Block diagram of fertigation system

2.2. Drip irrigation setup

The drip irrigation system consists of two reservoirs connected to PVC pipes; one reservoir containing tap water and the other containing a urea (Nitrogen) solution with a concentration of 30mg/L. As shown in Figure 5, each reservoir is connected to a solenoid valve to control the

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flow of liquid as needed. The outputs of the solenoid valves were connected to a T-joint connector whose output was connected to the drip line, which supplied a drip emitter through which water could be supplied to the crop.

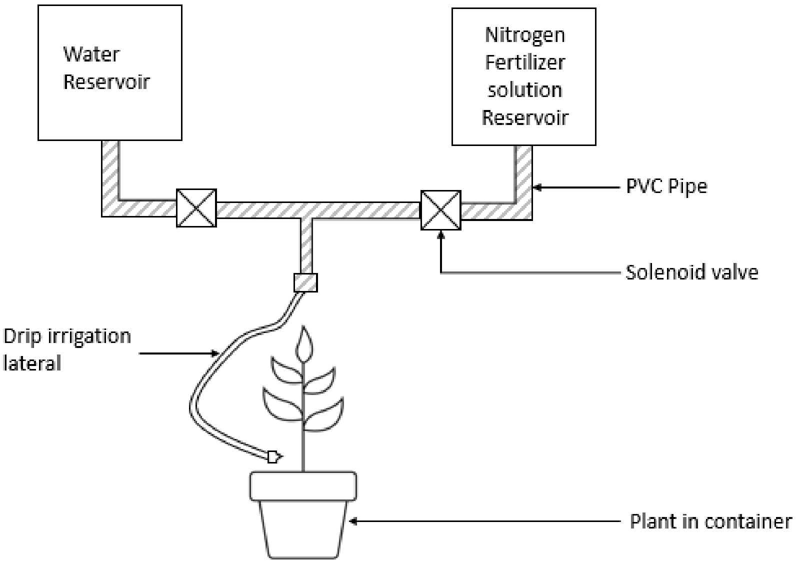

Figure 5: Diagram of the Drip Fertigation setup

The selected solenoid valve is a low-pressure valve with a minimum pressure requirement of 0.02 MPa. The minimum height of the water head for sufficient liquid pressure through the pipes was determined as about 15.8 cm. Also, the drip emitter used was designed to have a constant emission rate regardless of input pressure. All these factors ensure that there is no need for a pumping machine for this small-scale fertigation implementation.

2.3 Sensors

The soil moisture sensor used is version 2.0 of the Generic brand capacitive soil moisture sensor. It requires an input voltage of 3.3–5.5V and has an output voltage range of 1.2–2.5V. The output voltage of the sensor is directly related to the soil volumetric moisture content (VMC). The sensor was calibrated gravimetrically and the sensor value at the field capacity was determined. It was used to set the threshold for the supply of water to the soil.

The soil nitrogen sensor used was manufactured by JXCT-IoT. It has an input voltage of 10–30V and an output voltage of 0–5V. This output voltage has been calibrated to measure the concentration of nitrate-ion within a range of 0-1999 mg/kg. Both sensors were inserted vertically into the soil with the probes at a depth of about 8 cm.

2.4 Circuit design and construction

The circuit was implemented as shown in Figure 6. The board is powered by a 12V supply and is connected across a Variable voltage buck converter (LM2596) set to an output voltage of 6V to power the Arduino Nano through the Vin input of the board and also to power the 3.3V

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Linear voltage regulator (AMS1117). The ESP-01 module is powered by the 3.3V regulator and connected to the D10 and D11 pins of the Nano for serial communication between them. The soil moisture sensor and the soil nitrogen sensor are connected to pins A2 and A1 respectively to read the voltage of the sensor outputs. The soil moisture sensor and relay module are powered from the 5V pin of the Arduino board.

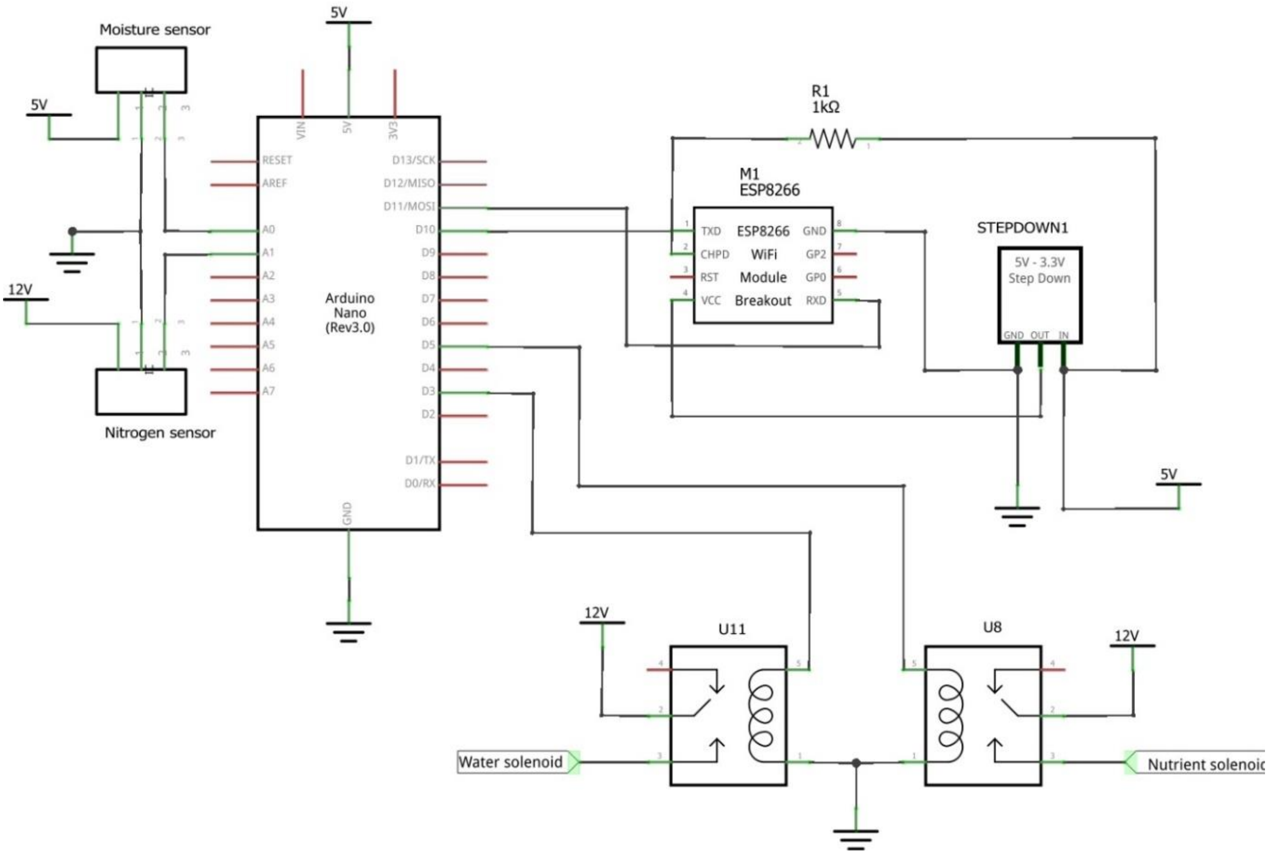


Figure 6: Control Circuit Diagram of the Fertigation system

The relay channels are connected to pins D0 and D1 of the Arduino board. The pins are toggled between 0V and 5V, to switch the required relay on and off, respectively. The solenoid valves and soil nitrogen sensor are powered by the 12V supply through the relays.

Once the circuit was tested on a breadboard and deemed functional, the microcontroller and ESP8266, ESP01, AMS1117 module, LM2596, resistor, and socket connectors were assembled and soldered on a circuit board. The board and the electronic components were then mounted in a PVC box.

2.5 Firmware algorithm and structure

The flowchart for the software developed is shown in Figure 7. Firstly, the microcontroller reads the output value of the sensors. The fertigation event is set to take place every morning before sunrise between 5 and 6 am. The microcontroller opens the solenoid valves if it detects that the values of soil moisture and nitrogen measured by the sensors are below the lower thresholds, and the supply stops when N_m and Θ are above the higher thresholds.

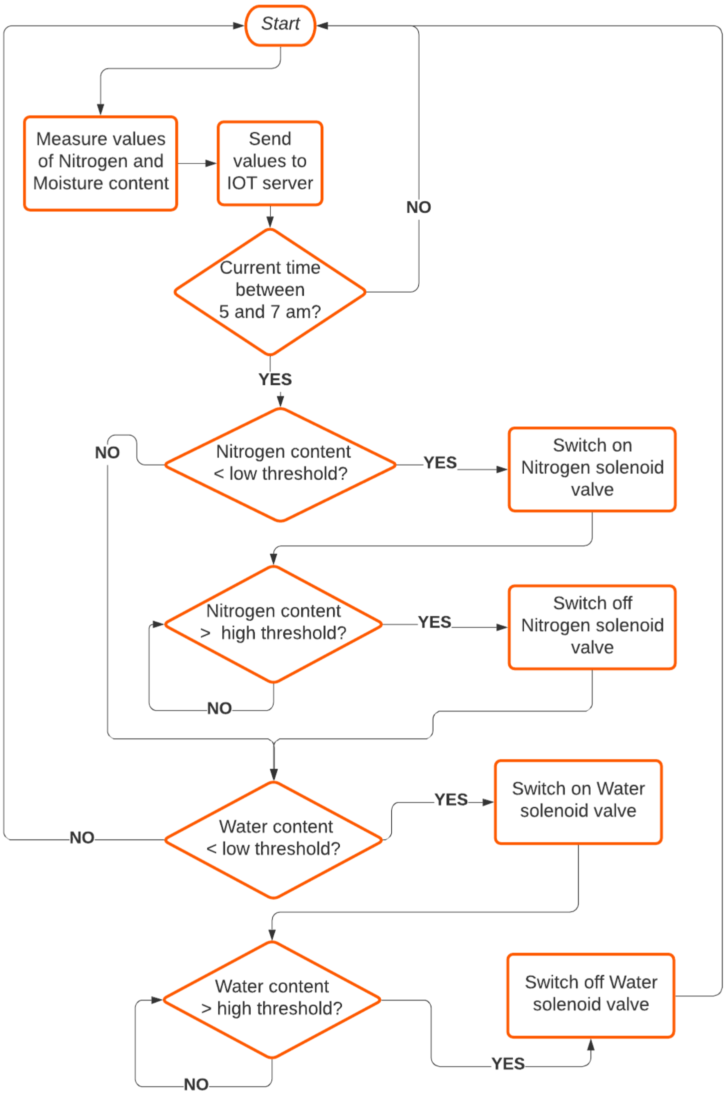


Figure 7: Firmware flowchart for controlling fertigation event

The soil moisture thresholds are set based on the values of VMC for Readily Available Water (RAW) and the Field Capacity (FC). As any amount of water supplied to cause the soil moisture content to rise above field capacity will be lost to deep percolation, the high threshold was set as the VMC at field capacity while the low threshold was set as FC-RAW.

For nitrogen fertilizer supply, the recommended soil nitrogen level for healthy growth of crops of a variety of vegetable crops is between 25 and 30 mg/kg (Heckman, 2002). Therefore, the lower threshold was set at 25 mg/kg and the higher threshold at 30 mg/kg.

Fertilizer application was set to occur before irrigation took place. This is because urea, if left stagnant in the pipes, can crystalize out of the solution, clogging the drip emitters. For this reason, water is needed to flush out the fertilizer solution from the pipes and drip irrigation system. The state of the solenoid valve and the measured values of the sensors are always sent to the server, and this enables monitoring of the fertigation system.

2.6 IoT platform GUI setup

Blynk (*Blynk IoT platform: for businesses and developers*) is an IoT platform that enables the connection of various hardware platforms to the internet and control via a mobile application or web dashboard. The platform consists of three main components. The Blynk mobile application or website dashboard is the first component that serves as an interface to control the hardware components and monitor the state of the sensors connected to them. The Blynk Server is the second component that serves as the link between the website dashboard and the hardware platform and on which data from the sensors is stored. The third component is the Blynk libraries, which are installed on the hardware platform and which allow the hardware platform to connect to the Blynk server and send and receive data from it.

To set up the web dashboard, first, virtual pins were created. These virtual pins allow the Blynk server to send data to the hardware platform and receive data from it. This data includes the state of the solenoid valves and the sensor output data. Widgets were then created on the dashboard. The widgets include switches, chart displays, and text display widgets. Four switches were created. Two of the switches displayed the state of each solenoid valve (whether it was open or closed) and were used to control the valve. The other two switches allowed the user to override the functionality of the system and control the valves manually. The text display widgets were used to display the current value of each sensor, while the graph display displayed the trend lines of each sensor's output. The same was done for the mobile dashboard through the Blynk mobile application. Figures 8, 9, and 10 show the IoT Platform GUI.

Chart settings

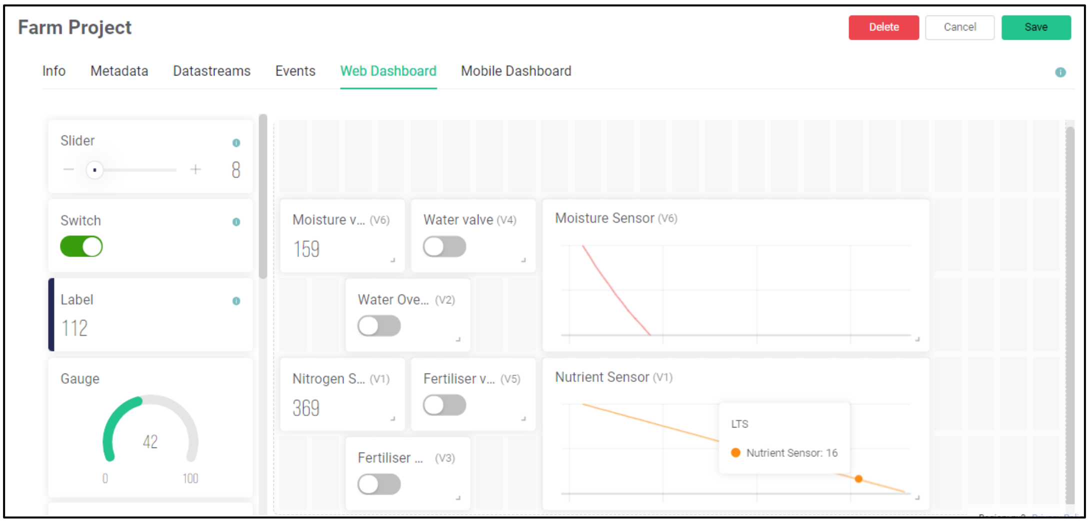
TITLE: Moisture Sensor

Datastreams: Moisture sense (... — AVG of

Enable Zoom: off

Show legend: off

Figure 8: Setting up a chart widget



Farm Project

Slider: 8

Switch: on

Label: 112

Gauge: 42 (0–100)

Moisture v... (V6): 159

Water valve (V4): off

Water Ove... (V2): off

Nitrogen S... (V1): 369

Fertiliser v... (V5): off

Fertiliser ... (V3): off

Nutrient Sensor (V1) — LTS, Nutrient Sensor: 16

Figure 9: Web dashboard layout

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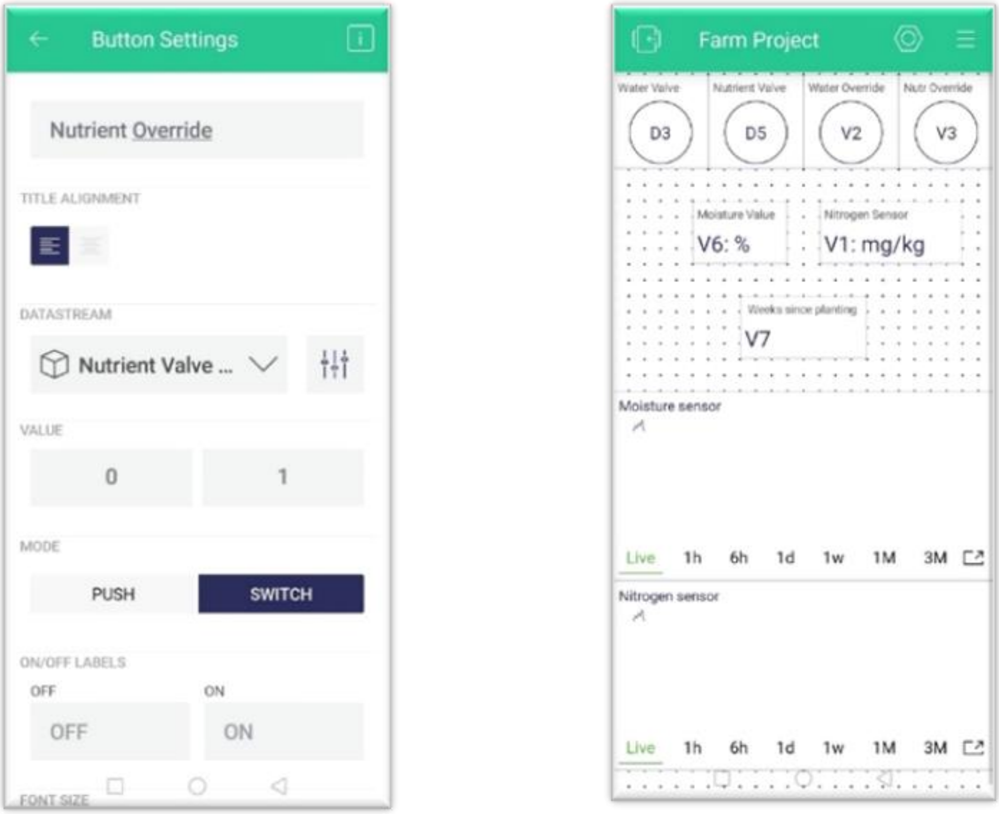

Button Settings

Nutrient Override

TITLE ALIGNMENT

DATASTREAM: Nutrient Valve ...

VALUE: 0 1

MODE: PUSH [✓ SWITCH]

ON/OFF LABELS
OFF: OFF
ON: ON

FONT SIZE

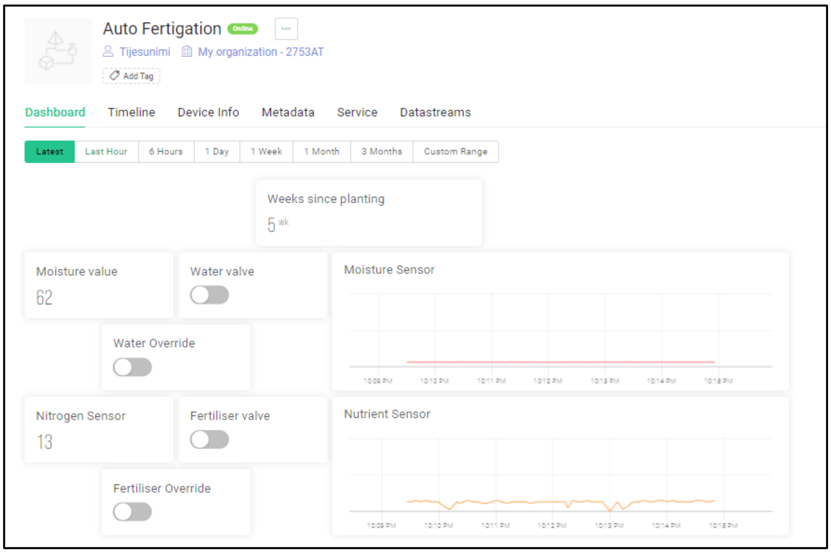
(i) Button widget creation page (ii) The dashboard layout

Figure 10: Setting up the mobile dashboard

3.0 Results and discussions

3.1 Blynk IoT dashboard

Dashboards were created for both mobile and web applications, which allowed the state of the system to be monitored over the internet and controlled, as shown in Figures 11 and 12 respectively. Override switches were also created to allow the solenoid valves to be manually controlled if the need arises. The graphs in the dashboard showed the trend lines of soil moisture and soil nitrogen over time. The values of the sensors could also be read on the text display or exported as CSV values.



Weeks since planting 5 wk

Moisture value 62

Water valve

Water Override

Nitrogen Sensor 13

Fertiliser valve

Fertiliser Override

Figure 11: Web Dashboard

Water Valve OFF

Nutrient Valve OFF

Water Override OFF

Nutr Override ON

Moisture Value 63%

Nitrogen Sensor 13mg/kg

Weeks since planting 5 Week

Figure 12: Mobile Dashboard

3.2 Controlling fertigation based on the sensor values

The sensor values increased commensurately when fertigation events occurred. This can be seen from the graphs in Figures 13 and 14. We see that the fertigation event took place between 5 am and 6 am and the moisture sensor readings increased from 29.2 to 40.1% and the nitrogen sensor readings increased from 18.8 to 30.1 mg/kg. It can be seen that the sensors could be used to effectively automate the fertigation process and monitor the soil state.

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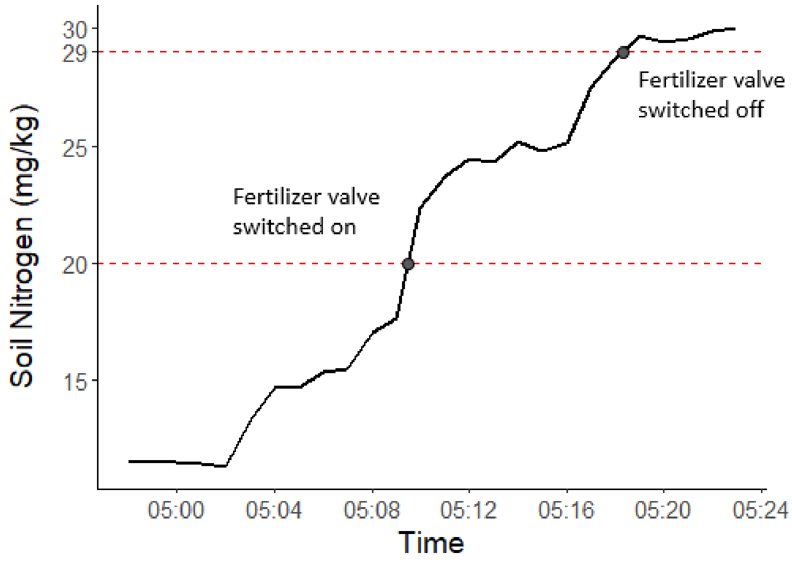
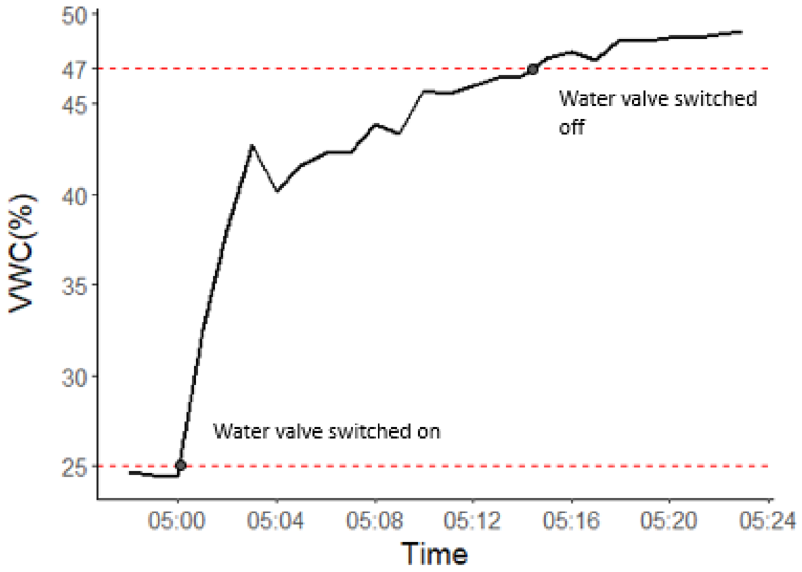


(i) Nitrogen sensor readings



(ii) Soil Moisture sensor readings

Figure 13: Trend of sensor readings during a fertigation event

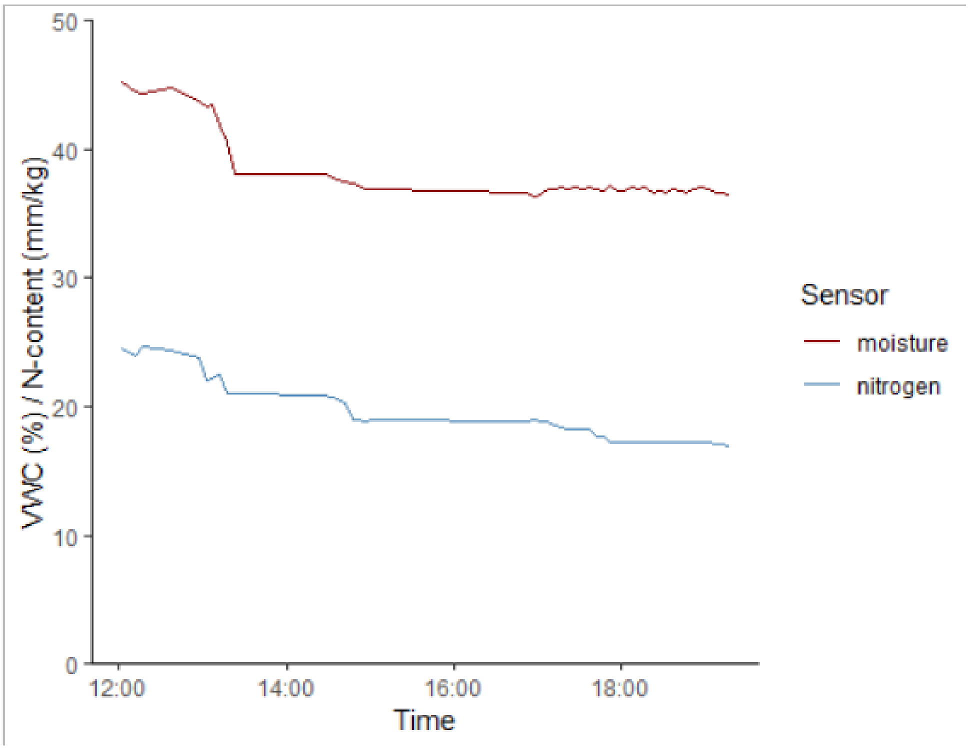


Figure 14: Experimental plots (soil moisture and Nitrogen concentration) acquired from sensors over a wide period

4.0 Conclusion

An automatic fertigation system that can be controlled and monitored remotely using IoT technologies has been developed. Crop irrigation and fertilizer application algorithms utilizing soil moisture and soil nitrogen sensors and linking the system to the Blink IoT platform have been implemented.

The huge positive potential of utilizing sensors to control fertigation systems and IoT platforms to monitor them has been demonstrated. Deployment of this system on a large scale will result in a reduction in farm waste, a highly efficient farm management process, and a reduction in labour costs. It will also lead to higher yields per unit of farm input resources used. The result of all of these is a net advantage for the farmer. It will increase the farmer's income and profit margins.

The only nutrient which was considered, measured, and controlled in the implemented fertigation system was nitrogen. However, there are other important nutrients needed for healthy plant growth. Two other major nutrients to be considered are potassium and phosphorus. Further research can also include the integration of the other three nutrients into the fertigation system.

5.0 Acknowledgement

5.1 Funding

None.

5.2 Presentation of the study, findings, and a portion of the work

A portion of the work done was presented in the 16th JKUAT Scientific, Technological and Industrialization Conference held on 24th -25th March 2022, (venue-Council Room, JKUAT & Virtually) under subtheme: Engineering technologies, ICT, built environment and infrastructure. Abstract paper (https://drive.google.com/file/d/1pCiWvu_euU7VfS-_Q4krXYViWSeFelml/).

5.3 Declaration of interest

There were none declared. This article's opinions, assessments, knowledge, and conclusions are exclusively those of the authors.

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