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RESEARCH

Development of a Solar-Powered Integrated Wireless Soil Moisture Meter

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Abstract

In this study, we developed a solar-powered integrated wireless soil moisture meter that can easily measure in situ soil moisture, soil temperature, and hydrogen potential (pH) using nature's solar energy. Knowledge of soil moisture content and other relevant soil-specific parameters is essential for irrigation scheduling, fertilizer selection, and fertigation. Also, considering that the electricity supply in some developing countries is either erratic or unavailable, this research aims to bridge the gap in electricity availability and ease of measurement and integrate more soil-specific parameters. The sensor system was developed using the frequency domain (FD) technique for fast response. These parameters were measured sequentially at an interval of about 5 seconds, with the readings displayed simultaneously on a Bluetooth-connected device (e.g., an Android phone) located about 50 meters away from the developed system. The different sensors are classified and adequately labeled to identify the parameter to be measured. The performance evaluation carried out indicated a reasonably functioning device that is cost-effective. The results obtained showed that the system was resourceful as it not only measured the parameters of interest (soil moisture, temperature, and pH) but also gave a prompt response in measurement and transmission. Overall, the developed wireless soil moisture meter provides instantaneous data on pH, moisture, and temperature circulation across soil layers. The system is promising as it can be integrated into large-scale automated irrigation systems for agricultural lands.

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Statement of Sustainability: The integration of solar power into the soil moisture measurement system demonstrates a commitment to reducing the consumption of fossil fuel-based energy and minimizing carbon emissions. By using solar energy as the primary power source, this research aims to contribute to the transition to a low-carbon economy. Solar power is a clean, renewable, and abundant energy source that can be used to power various agricultural applications. The wireless functionality of the soil moisture measurement system is another aspect that is in line with sustainability principles. By eliminating the need for extensive wiring and infrastructure, this wireless system reduces material consumption, installation costs, and environmental impact.

1. Introduction

Soil moisture is an indispensable component in addition to the other two components (soil minerals or solids and air) that make up the three-phase system of the soil. For effective irrigation management, soil moisture assessment is essential (Susha et al., 2014; Dong et al., 2013; Jiang et al., 2017). The availability of soil moisture greatly affects crop growth and yield. Similarly, soil temperature and hydrogen potential (pH) are also vital parameters that help in crop selection and effective irrigation practice for a particular field, as well as crop development, growth, and yield. Soil moisture status also has a great influence on engineering, geological, agronomic, hydrological, and ecological (Entekhabi et al., 1996; Koster et al., 2003; Koster et al., 2010), biological soil behavior and climatological processes (Taylor et al., 2012; Robinson et al., 2008; Lin, 2010; Banwart et al., 2011; Lin, 2011).

To effectively measure soil moisture, researchers have developed numerous techniques that can be classified into classical and modern techniques for laboratory and in situ measurements (Susha et al., 2014; Wang et al., 2022). The classical techniques are thermogravimetric and calcium carbide techniques, while the modern techniques are resistivity-based methods (Song et al., 2012; Mosuro et al., 2012), dielectric techniques, namely Frequency domain reflectometry (FDR) (Al-Asadi and Mouazen, 2014), Time domain reflectometry (TDR) (Janik et al., 2015), and capacitance technique (Susha et al., 2014), among others. Several electrically based soil moisture measurement systems have been successfully applied in fields such as geophysical survey (Jaria and Madramootoo, 2012; Lehmann et al., 2013), water quality (Razman et al., 2023), and agronomy (Pakparvar et al., 2016; Wang et al., 2015; Baghdadi et al., 2014). However, the commercial application of resistivity-based sensors (e.g., land mapper, which requires software to understand the vertical electrical behavior of soil) is challenging due to high cost, lack of integrated data acquisition capabilities, and availability (Jiang et al., 2017). In addition, these techniques could not measure other important variables such as soil temperature, pH, salinity, mineralogy, organic matter content, and porosity (Susha et al., 2014; Uppal et al., 2023;).

It has been confirmed that the sensor system is a resourceful technology and is used in almost all aspects of human endeavors (Polo et al., 2015). Agriculture is one of the areas where sensors and their networks have been used resourcefully (Aqeel-ur-Rehman et al., 2014; Polo et al., 2015; Salam et al., 2019). The need for efficient resource and environmental management has prompted the use of the Internet of Underground Things (IOUT) for various purposes in precision agriculture (Akyildiz and Stuntebeck, 2006; Bogena et al., 2010; Markham and Trigoni, 2012; Dong et al., 2013; Abrudan et al., 2016; Liu et al., 2016). IOUT is capable of some monitoring functions such as precision irrigation and assisted navigation (Silva and Vuran, 2010a; Silva and Vuran, 2010b; Zhang et al., 2017; Falana and Durodola, 2022); sports field maintenance (Zhang et al., 2017), border monitoring (Akyildiz et al., 2009; Sun et al., 2011), landslide and pipeline monitoring (Akkas, 2017; Guo and Sun, 2014; Vuran et al., 2018), fertilizer concentration in soil (Goumopoulos et al., 2014), and assessment of soil moisture, temperature, pH, and salinity, as well as providing real-time facts about environmental factors such as wind, rain, and sun (Salam et al., 2019). In the past, techniques such as gypsum sensors and tensiometers were used to measure soil moisture, but their drawbacks such as unsatisfactory response as well as errors due to hysteresis between wetting and drying led to the search for a better technique (Jiang et al., 2017; Schwamback et al., 2023). Remote sensing technologies (e.g., radars and radiometers on board satellites) have also been used to measure soil moisture, but drawbacks such as low resolution on the order of square kilometers affect their data collection (Wu et al., 2014).

Conversely, the application of in-situ sensors that can provide measurement data for a larger radial distance of more than a few square meters can provide a better measurement (Zhou et al., 2019). Therefore, the attention given to wireless technologies over the years has led to significant advances in the field (Rashid and Rehmani, 2016; Wang et al., 2006; Patrizi et al., 2022). Advances in the development and application of various types of wireless technologies ranging from Infrared Data Association (IrDA), which uses infrared light for short-range, point-to-multipoint communications, to Wireless Personal Area Network (WPAN) for short-range, point-to-multipoint communications, such as Bluetooth and ZigBee, to mid-range, multi-hop Wireless Local Area Network (WLAN), to long-range cellular telephone systems, viz: Global System for Mobile Communications (GSM) and General Packet Radio Service (GPRS), and Code Division Multiple Access (CDMA) (Wang et al., 2006; Polo et al., 2015).

The objective of this work is to develop a solar-powered integrated wireless soil moisture meter that can accurately measure soil moisture, soil pH, and soil temperature, and wirelessly transmit the data to a Bluetooth-connected device such as an Android phone over a reasonable distance using a wireless Bluetooth module instead of requiring external cables, and its field performance evaluation was conducted. This technology has the potential to revolutionize agriculture by providing real-time soil moisture information that can help farmers optimize irrigation and improve crop yields while conserving water resources. This study is unique in the following ways: the development and use of wireless sensor networks, solar energy as a renewable power source, the integration of temperature and pH in the measurement, and its ability to provide real-time information without significant delay time.

The study includes, first, a brief description of the different techniques used to determine the soil moisture content for the sensor system, as well as the relevance of the selected variables (soil moisture, pH, and temperature) in crop production. The second section also describes the study area, followed by a description of the component materials used and the method employed. Subsequently, the description experiments for the calibration of the moisture, pH, and temperature sensors were carried out and the results obtained in the cited experiments are conferred. Finally, the conclusions of the study, the prospects of incorporating this system for irrigation management, recommendations for future needs, and further studies are stated.

2. Material and Methods

2.1. Description of the Study Area

The Federal University of Technology, Owerri (FUTO) is the premier Federal University of Technology in the South-East and South-South geo-political zone of Nigeria. It is located next to the Federal Polytechnic, Nekede, along Naze-Obinze Road at the western end of Owerri. FUTO is located at approximately 5°30' N latitude and 7°10' E longitude in the south-eastern region of Nigeria and has an altitude of about 55.7 m above sea level (Emma-Okafor et al., 2016). It is bounded by the communities of Eziobodo, Umuchima, Ihiagwa, and Obinze. The climatic record of the area has a pronounced wet and dry season influenced by the common maritime air mass it experiences. The mean annual rainfall is about 2,500 mm and is bimodal with the highest values in July and September. The area records mean daily minimum and maximum temperatures between 19–24 °C and 28–29 °C, respectively, as well as an average relative humidity of about 80%; the area also records a relatively longer rainy season that lasts from April to November, while the hottest period is recorded from January to March. Harmattan is observed in the area from late December to late February (Ajibade et al., 2020).

The area has characteristic moderately humus-rich topsoil with predominant semi-deciduous forest, which has been modified by increased agricultural and other anthropogenic activities (Onweremadu et al., 2008; Ogbuagu and Okoli, 2013). Ultisols of characteristic deep porous red soils derived from sandy deposits in the coastal plain that are highly weathered, coarse-textured, low in mineral reserves, and natural fertility generally dominate the soils in the FUTO area (Onweremadu et al., 2007). The high temperature and humidity greatly promote plant growth, as the tropical rainforest peak vegetation can be found in the area. The FUTO area cuts across the Otamiri River (a major watercourse in Owerri), on which the surrounding population depends for domestic, fishing, and artisanal sand mining activities. The Otamiri River runs through the campus to the suburbs and then to the adjoining Rivers State, where it has its first confluence with the Oge-Ochie River, followed by the Imo River, before draining into the Atlantic Ocean.

2.2. Materials Procurement

The design and fabrication of a portable, solar-powered, wireless soil moisture sensor system requires careful selection of the best materials and wise use of the selected materials to achieve the design objectives. In this project, the affordability of the system to local farmers was considered. This guided the selection of inexpensive yet efficient components that could serve the purpose of the work. Few of the components used were imported, while others were locally sourced, and the actual prices could not be reported due to the common unstable exchange rate of currencies. The developed system cost about $80; therefore, considering the three built-in parameters of concern that this system measures, the choice of components of the system, and the overall comparison of our developed system with other already made imported meters, it can be asserted that our system is relatively cost-effective for local farmers. The following materials were used in the design and manufacture of the system: solar panel (10W, 0.58A, 17.4V), wireless communication module (HC-05 Bluetooth), microcontroller (Arduino), memory chip (FLASH, 1 megabyte), battery (LED Acid, 12V, 9.2Ah), frequency domain probes, level converter, temperature, pH, and moisture probes, electronic interfaces, metal shield (frame) with tripod stand (ø8 cm, 120 cm long; tripod stand, 44 cm), and coaxial cable.

To develop the meter, the frame was constructed by welding. The Arduino was connected to a computer with a USB cable and then programmed to assign the appropriate data to the parameters of interest according to the literature and the results obtained in the laboratory. After programming the Arduino, the components, including the display unit, the Arduino, Bluetooth, and the battery, were placed in the control box and properly connected to protect them from excessive sunlight and rain. The solar panel and sensors were connected at the top and bottom, respectively, as shown in Figure 1a, b.

2.3. General Description of the Designed Prototype

2.3.1. Arduino Uno Microcontroller

Arduino is an open-source program used to build electronic tasks. It includes a physical programmable circuit board (microcontroller) and software or an integrated development environment (IDE) that runs on a computer and can write and upload computer code to the physical board. Unlike other programmable circuit boards, the Arduino does not require a dedicated piece of hardware (known as a programmer) to load code onto the board; instead, you can simply use a USB cable to do so. In addition, the Arduino IDE includes a beginner's version of C++, making it easier to learn the program. The Uno is one of the most popular boards in the Arduino family and is a good choice for beginners. The flexibility and low cost associated with the Arduino make it an excellent program for many users. In this project, the Arduino serves as the heart of the controller unit. It receives signals from all the sensors, processes them, and stores their values.

2.3.2. Liquid Crystal Display (LCD)

LCDs are devices that display the output of the Arduino microcontroller. They are of two types, namely: graphic LCDs and character LCDs. In this study, we used a 16 × 2 green character LCD (16 columns and 2 rows) to display messages as well as moisture, temperature, and pH values as they are read from the sensors.

2.3.3. Wireless Communication (HC-05 Bluetooth) Module

The HC-05 Bluetooth Module is a trendy component capable of adding two-way (full-duplex) radio effectiveness to devices. It is used to connect two microcontrollers such as Arduino or any device with Bluetooth functionality such as a phone or laptop. USART is used to communicate in the module at baud rates of 9600 and above; therefore, interfacing with microcontrollers that support USART is easier. For this project, analog soil moisture, temperature, and pH meters were used with a simple, convenient, and practical connection and features designed specifically for Arduino controllers. Each has an LED that acts as a power indicator, a BNC connector, and a sensor interface. It should be noted that if pre-programmed, getting the pH, temperature, and moisture values will be more accessible.

2.3.4. Sensors

In this work, three spear-shaped sensors were used, including moisture, temperature, and pH sensors, each capable of measuring the desired soil parameters. These sensors are waterproof and can measure parameters within a few seconds. While the moisture sensor measures the volumetric moisture content of the soil, the temperature and pH sensors measure the temperature profile of the soil and the pH of the soil, respectively.

2.4. Operation and Data Collection Methods

Measuring soil moisture has always been a challenge for farmers in terms of time and accuracy. In addition, the need to consider other soil-related parameters (pH and temperature) that are important for crop growth and yield was identified in the design of this project. These and other attributes made this project stand out from the many existing meters. In this project, an FD-based impedance measurement approach was used, and the following design considerations were considered: soil and environmental condition/field analysis, initial and maintenance costs, portability, power consumption, speed of measurement, coverage and volume of measurement, and accuracy. The system was deployed on a farm located at the FUTO, Nigeria. Measurements were taken at four (4) different locations at different depths (displacements) of 5, 10, 15, and 20 cm. During this experiment, the existing moisture content was measured. Then, 0.5 L of rainwater was added to the four different points and depths, and measurements were taken after 10 minutes. After the Bluetooth connection, the operating sequence of the device in the work mode takes 5 seconds to display each parameter and then switches to the measurement of another parameter, 2 seconds delay time to transmit the data to the Bluetooth-connected Android phone, making it about 20 seconds for a sampling process.

The pictorial view of the developed system is shown in Figure 1a, b. Figure 1c is the orthographic view of the system showing the parts in detail, while Table 1 describes the components of the system. The solar panel serves as the primary power source and the generated power is supplied to the system through a cable connected to the central unit in the control box. To ensure a constant power supply for optimal system operation, a rechargeable battery is also embedded in the control box to act as a backup power source during periods of low or no sunlight. The system includes a display unit to show the result of the measured parameters; it also includes a switch to activate and deactivate the system. A hollow mild steel tube is used for the structural component of the system (frame and tripod), while the tripod ensures a firm stand on the ground during measurement. The frame and tripod are assembled by simple welding, while the control box is attached with bolts and nuts. The cables for the probes are fed from the control unit through the hollow tube and extended to the bottom where they are inserted into the ground directly under the tripod. The probes are easily inserted into the ground by hand.

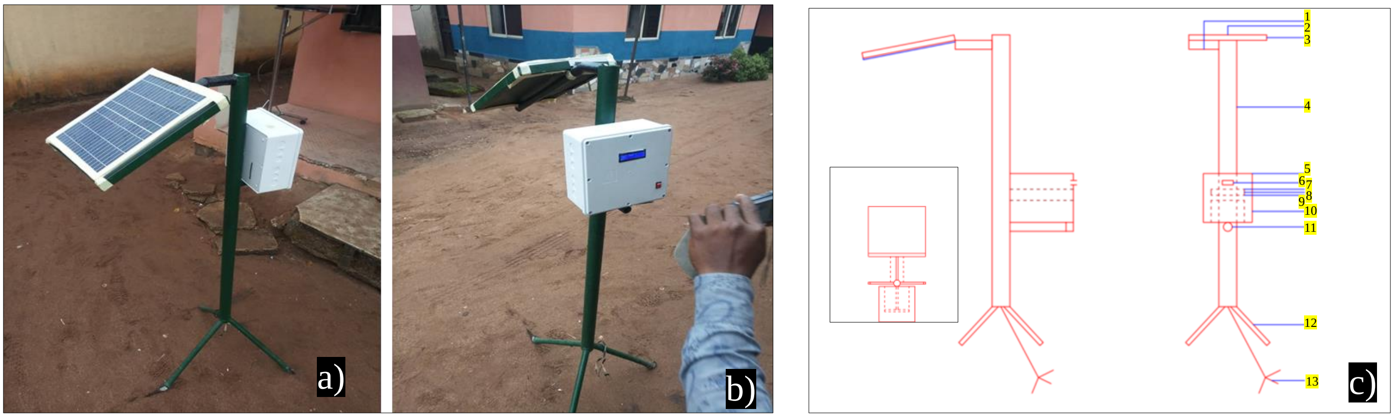

Figure 1. a) and b) Pictorial views of the system; c) orthographic view of the system.

Table 1. Description of the system components.

Part No	Quantity	Description	Dimension	Material	Remarks
1	1	Tray link	Ø4cm; 48cm long	Mild steel	Panel support
2	1	Solar panel	35cm × 28.5cm × 2.5cm		Charging unit
3	1	Panel tray	36cm × 30cm	Mild steel	Panel support
4	1	Frame	Ø8cm; 120cm long	Mild steel	Structural support
5	1	Control box	22cm × 22cm × 12cm	PVC	Control unit
6	1	LCD	5cm × 2cm		Display unit
7	1	Central unit			Control board
8	8	Bolt	Ø0.2cm	Mild steel	Coupling component
9	1	Switch	1.5cm × 1cm	PVC	On/Off unit
10	1	Battery	15cm × 10cm × 6cm		Power unit
11	1	Box anchor	Ø4cm; 12cm long	Mild steel	Box support
12	1	Tripod Stand	Ø4cm; 44cm long	Mild steel	System support
13	3	Probes	5 cm long		Sensing component

3. Results

3.1. Calibration of the Soil Moisture, Temperature, and pH Meters

Soil samples obtained from the field were used for site-specific grading in the laboratory before the field trial to ensure measurement accuracy. Specifically for moisture content, soil samples were collected from the farm area and the oven drying measurement method was carried out in the laboratory to obtain the result, which was later used to calibrate the moisture sensor using the Arduino on the computer. Regarding soil temperature and pH, the information about their wide range of fluctuations in all soil types, as obtained from other works in the literature, was used to calibrate the soil temperature and pH sensors. Considering the analysis of the soil heat energy balance, it is confirmed that the temperature varies both daily and seasonally, with the former varying and fading out around a few tens of centimeters, while the latter varies at greater depths; its variation and rate of transmission to the earth is dependent on the thermal properties of rocks in the soil, radiation, and latent heat exchange at the soil surface (Nwankwo and Ogagarue, 2012). Nwankwo and Ogagarue (2012) suggested that the average temperature for all soil types is 28.7 ºC. Furthermore, it is worth considering soil pH as another factor whose status should be understood for sustainable practices in fertilizer selection and application, irrigation, and crop selection. Due to the partial movement of nutrients such as phosphorus, potassium, calcium, magnesium, zinc, and lime through the soil, the pH of the soil is usually affected over depth. Proper tillage is recommended to mitigate this (Anderson et al., 2010). In general, the pH range of most soils is between 3.5 and 10, and the higher rainfall areas have a natural range between 5 and 7, while the drier areas are characterized by a pH range of 6.5 - 9. From this pH-based analysis, soils are categorized as neutral soils (6.5-7.5), alkaline soils (>7.5), acidic soils (<6.5), and highly acidic soils (<5.5) (USDA, 2017). These cited facts were used in the programming of the Arduino microcontroller. Calibrations were performed to indicate different parameter ranges for different soil conditions. The calibrations are listed in Table 2.

Table 2. System calibration of soil moisture, temperature, and pH on different soil conditions.

Moisture			
Tested soil type	Measured soil moisture value (range)	Soil condition interpretation	Percentage of soil moisture (%)
No condition	< 5	-	0 – 2
Dry	≥ 5, < 60	Dry soil	2 – 29
Balance	≥ 60, < 70	Balance soil	30 – 49
Wet	≥ 70, < 100	Wet soil	50 – 100
Temperature			
Tested soil type	Measured soil moisture value (range)	Soil condition interpretation	Percentage of soil moisture (%)
No condition	< 20	-	0 – 20
Cold	≥ 15, < 25	Cold soil	15 – 24
Balance	≥ 25, < 35	Balance soil	25 – 35
Hot	≥ 35	Hot soil	> 35
Potential of Hydrogen (pH)			
Tested soil type	Measured soil moisture value (range)	Soil condition interpretation	Percentage of soil moisture (%)
No condition	< 1	-	0 – 1
Acidic	≥ 1, < 6	Acidic soil	1 – 5
Neutral	≥ 6, < 9	Neutral soil	6 – 8
Alkaline	≥ 9, ≤ 14	Alkaline	9 – 14

3.2. Performance Evaluation of FD Sensor in Displacement

The values obtained for the parameters of concern (moisture, temperature, and pH) are shown in Table 3. Figure 2 is the plot of the parameters of concern (soil moisture, temperature, and pH) versus depth. The pre-existing moisture is commonly used in Figure 2 because it showed significant variation over depth, while the following moisture readings were obtained after the addition of rainwater, which was primarily used to obtain the soil pH of the various points when there was no pH measurement due to low moisture content.

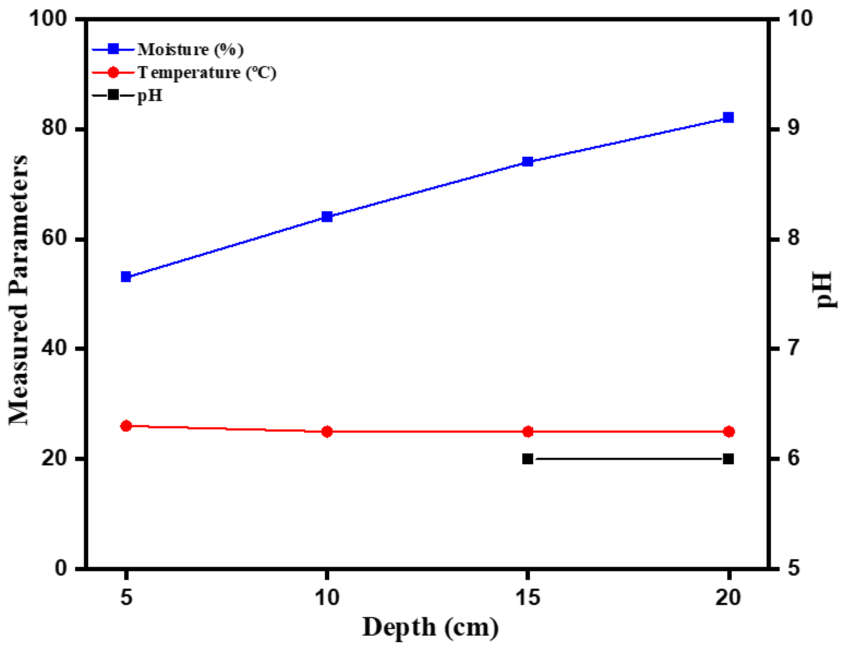

Figure 2. Graph of the parameters (pre-existing soil moisture content, temperature, and pH) against depth.

Table 3. Performance evaluation of FD sensor in displacement and different points.

Number	5 cm Displacement			10 cm Displacement			15 cm Displacement			20 cm Displacement		
	M	T	pH	M	T	pH	M	T	pH	M	T	pH
Pre-existing (1)	53	26	-	64	25	-	74	25	6	82	25	6
2	78	26	6	100	25	6	92	25	6	100	25	6
3	91	26	6	94	25	6	90	25	6	95	25	6
4	90	26	6	91	25	6	100	25	6	93	25	6
5	87	26	6	90	25	6	97	25	6	98	25	6

M: Moisture (%); T: Temperature (ºC).

4. Discussion

This study was carried out to determine the soil moisture content, pH, and temperature at different soil depths and agricultural areas (cultivated or uncultivated). All the design and implementation of this meter are explained. The meter gives some data on soil moisture value range, percentage of soil moisture, and soil condition in terms of temperature and pH. This meter incorporates some features and functions that distinguish it from others. Decoding the data obtained provides a better understanding of the physical properties of the soil, more than such studies that focus on soil moisture determination only. Therefore, this study provides better knowledge for managing the crop growing process and resource management. The results of the study showed that if there is enough sunlight, the battery needs 2 to 3 hours to be fully charged in summer and a longer period of hours or days to be fully charged in winter. Most of the products used a chemical kit to determine soil moisture, and some of the devices required complex connections before measurements could be made. The power consumption of this system is low considering the power rating of the components: the LCD, sensors, and Bluetooth module of approximate ranges of 1 mA, 13 mA, and 40 mA, respectively. This meter is durable, inexpensive, easy to use, and can be left in the ground for long periods because the system's power is generated by a solar charging system. During the experiments with the device, it was observed that the pre-existing moisture level varied more and more with increasing depth. This shows that the top layer of the soil has the lowest moisture content due to evaporation from heat exchange between the soil and the atmosphere. Below this layer, the moisture content of the soil is maintained by the action of capillarity and adhesion. It was also observed that the greater the depth, the higher the clay and silt content, which holds more moisture against the sandy topsoil according to the USDA (2017) soil classification.

Similarly, it was observed that the pH sensor could not detect the soil pH at points with lower moisture content (< 70%); therefore, we added harvested rainwater to the Depth where it occurred for the sensor to detect the pH reading. It was found that the meter could read the pH of the soil when the moisture content (MC) was above 70%. Therefore, harvested rainwater was added where the meter could not get a pH reading while we observed MC reading below 70%. This was just an initiative taken as a trial step to see if it was possible to get a pH reading after adding rainwater, which later worked. The pH readings did not vary with depth in most cases. The different depths of evaluation gave a typical value of six (6), indicating that the area of the experiment is a high rainfall area according to the classification made by Anderson et al. (2010) (in higher rainfall areas the natural pH of soils typically ranges from 5 to 7, while in drier areas the range is 6.5 to 9). Furthermore, the temperature variation across depth was not large (between a range of ±1 and ±2). However, at 5 cm depth, the temperature was higher (26 ºC) against greater depths of 25 ºC. This could be due to the influence of the ambient temperature at such a shallow depth, affecting the soil heat exchange. To this end, more research and development are urgently needed to facilitate technological innovation to improve food security (economic growth) and environmental sustainability in the future.

5. Conclusion

In this study, the practicality of integrating soil moisture, pH, and temperature sensors as a system that can sequentially determine their respective parameters at infinitesimal time intervals and simultaneously transmit the obtained data to a Bluetooth-connected device (e.g., Android phone) in the farmland environment was determined. The sensors can be inserted at different soil depths and provide instant data on the variation of parameters across soil layers. Thus, the system can be helpful in various computerized irrigation systems for farmlands; similarly, for power supply and to eliminate the technical stress involved in removing the battery for charging, especially in developing countries, the solar panel is integrated into the system. Moreover, since pH and temperature are integrated with its measurement, it would be helpful to farmers and irrigators in their choice of irrigation scheduling, fertilization, and fertigation. This provides a technological basis for the advanced study of wireless networks for monitoring more soil-specific parameters, including salinity, mineralogy, etc., over large areas of farmland. Also, the inability of the system to measure soil pH at moisture levels below 70%, while detecting pH after rainwater has been added to the soil, and the need to describe the impact zone within the soil mass for which the system takes a measurement, require further study.

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Data/Supplementary Information Availability: Not applicable.

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