A technology review and field testing of a soil water quality monitoring system

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Abstract. Soil water quality is one of the most influential factors in ensuring the productivity of agricultural farms. Soil water quality and soil quality are hugely dependent on each other. Hence, it is essential to have a clear understanding of the essential soil quality parameters and the existing technologies to detect those parameters. This paper briefly discusses the vital soil quality parameters for their significance towards fostering sustainable agriculture. Moreover, a technology review of recent studies has been critically analyzed, and their strengths and weaknesses have been addressed. Moreover, an Internet of Things (IoT)- enabled low-cost, low-power soil monitoring system has been proposed to overcome the drawbacks of the existing technologies. The initially developed system has been deployed in a residential garden for preliminary testing and results. However, the findings of the proposed system satisfy the expected outcome as the testing soil parameters, such as soil moisture content and temperature, vary accordingly with the increase in depth underneath the surface. Also, environmental parameters such as ambient temperature, carbon dioxide and humidity vary expectedly over day and night. Data obtained from this system will be beneficial to derive realistic water-balance estimations and sustainable agriculture decision-making.

Keywords: Groundwater, soil quality parameters, IoT, smart sensing systems

1 Introduction

Groundwater is an essential water source to meet the community's needs in many countries [1]. It helps supply water in urban and rural areas and reduces surface water scarcity [2]. The leading causes of groundwater pollution, however, are thought to be anthropogenic activities, including farming, industrial effluents, and improper waste disposal on the land surface [3,4]. Global crop production has recently seen a progressive increase in the heavy use of agrochemicals (fertilizers and pesticides) in agricultural fields [5]. Agrochemicals are used by both large- and small-scale farmers to grow crops and boost agricultural yields. They have thus increased the rate at which they apply fertilizers and pesticides, which may affect the groundwater quality. However, other variables affect groundwater quality, including geological formation, soil type and permeability, depth to the water table, precipitation levels, the aquifer's hydraulic conductivity, and the solubility of the rock components [6]. Groundwater is susceptible to contamination from various sources, including industrial and agricultural operations, changes in land use, and other activities. Poor groundwater management can result in multiple severe issues with water quality, including water that is unfit for eating by humans or other animals [7]. The primary groundwater quality parameters are salinity, acidity, nutrients, and contaminants such as heavy metals, industrial chemicals, and pesticides. Poor groundwater quality can have significant economic effects by lowering agricultural and horticultural productivity [8]. When polluted groundwater enters waterways and wetlands, it may harm the environment and affect ecosystems that depend on groundwater. Moreover, poor groundwater quality can seriously end people's health [9].

Groundwater quality can be managed by employing Internet of Things (IoT)-enabled sensing systems to track soil quality indicators such as moisture, temperature, pH, nitrate, phosphate, potassium, salinity, and organic carbon [10]. Storing the data into the cloud server and sharing those with specialists will enable farmers to receive professional advice from anywhere in the world. A typical schematic of significant groundwater components is shown in Fig. 1 [11]. For this reason, agricultural nations like Australia, New Zealand, Japan, and the USA are now interested in fusing technology with agriculture. It is essential to have a clear understanding of the crucial aspects of soil quality and their effects to develop and implement intelligent agricultural systems.

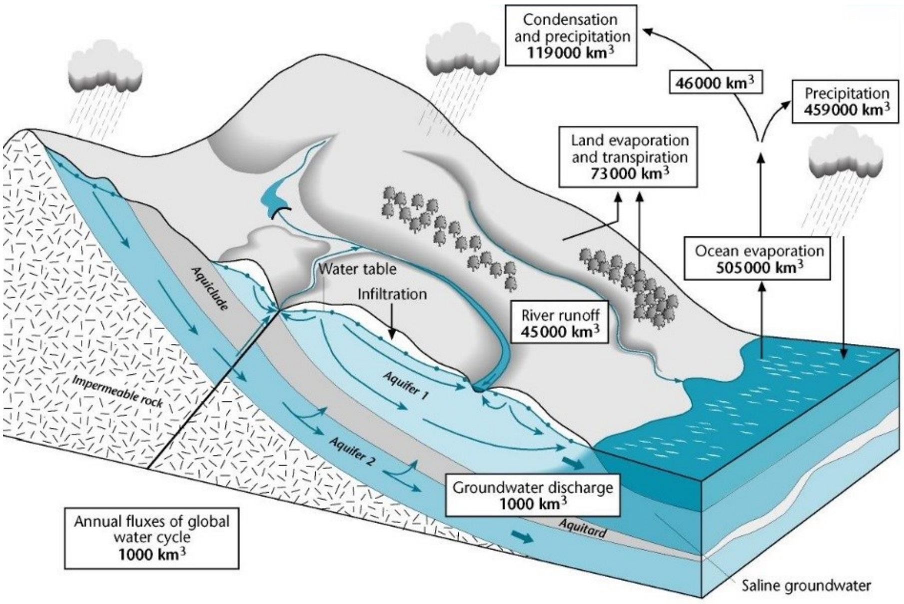


Fig. 1. Groundwater components in a typical hydrological cycle [11].

This review article addresses the factors that affect groundwater quality, the ideal value for each parameter to ensure sustainable agriculture, and the technologies currently used to measure those parameters. It also proposes a cost-effective, energy-efficient, innovative sensing system for intelligent farming. Adapting this system will help farmers identify issues affecting farm conditions and make decisions to boost output effectively based on real-time data.

2 Essential Soil Water Quality Parameters

More than seventy per cent of the earth's surface is comprised of water, which is fundamental to life on this planet. Typically, the soil inside the earth's surface is composed of a three-phase system that is solid (soil particles), liquid (water and solutes), and gas (air). When the soil is void of water, all the pores are filled with air; however, if the air is replaced with water, the soil is said to be saturated. When soil is water-saturated and the atmosphere is excluded for long periods, many soil organisms suffer from a lack of oxygen [12].

The relationship between soil and water is essential to soil organisms and plant life. Not only does soil water contain various chemicals that influence soil's physical, chemical, and biological properties, but its flow and retention inside the soil also play a vital role in the soil formation process over time [13]. This section will highlight some essential soil water quality parameters useful in water balance investigation and precision agriculture.

2.1 Soil Moisture Content

The soil moisture content is a prime environmental variable directly related to the process of evapotranspiration. Its measurement helps determine potential soil conditions for scheduling irrigation and crop yielding activities, predicting flood conditions, forecasting precipitation patterns, and eliminating wasteful water use. There is a range of scientific methods of measuring soil moisture content. Many devices have been developed over time for indirect soil moisture measurement, such as time domain reflectometry, the dielectric constant of soil, neutron scattering, thermalization of H atoms in soil, low-cost moisture resistance cells, electrical conductivity electrodes, watermark sensors, and more [14]. In our prototype system, we have used analogue capacitive soil moisture sensors at different depths to detect the moisture content in the soil.

2.2 Soil Temperature

Soil temperature is a crucial factor in all physical, chemical, and microbiological processes in soil. Especially in the evaporation process, it directly affects the water movement patterns and distribution in soil, aeration in pores such as the conversion of liquid to gaseous water in the form of water vapors. It also has a good influence on agriculture crop breeding and optimum vegetation capacity. Optimum temperatures are best suited for healthy soil organisms as it prominently increases the nitrification rate [15]. Electrical-resistance digital thermometers are widely used in soil monitoring applications to measure temperatures within the soil, depending on the degree of precision required. In our prototype system, we have used one-wire digital temperature sensors to find out inside soil temperatures.

2.3 Soil pH

The pH value is a defining quality parameter that controls the availability of essential chemical nutrients in the soil, which is helpful for optimum crop productivity and land treatment. It is a measure of hydrogen ions (H+) concentration that determines the acidic or alkaline nature of the soil. Though it usually ranges from 1 – 14 for different crop types, the ideal range is between 5.5 (slightly acidic) and 7.5 (slightly alkaline) for most crops' maximum productivity. Moreover, soils that face heavy rainfall are usually acidic since rainwater being somewhat acidic, reacts with carbon dioxide in the atmosphere to form carbonic acid and percolates through pores inside soil as bicarbonates which are critical for determining growth [16,17]. The most common method for soil pH measurement is the colorimetric test using the test kit.

2.4 Soil Nitrate

A type of inorganic nitrogen (N) found in soils naturally is called nitrate (NO_3^-). Some earth sources are exudates from growing plants, chemical fertilizers, animal manure/compost, rainfall, and lightning [18]. The building blocks of life, nucleotides, amino acids, and proteins, including nitrogen, are among the required nutrients for plants. Only a few plant species can form symbiotic relationships with particular bacteria, which allows them to use atmospheric nitrogen. The resources for the other species are found in the soil, which contains nitrogen in various forms [19]. For instance, the soil solution might include several types of organic N, including soluble proteins or amino acids produced by proteolytic processes. In temperate climates, inorganic N forms predominate, and fertilizers are frequently delivered as nitrate, ammonium, or urea. Nitrate levels between 20 ~30 mg/Kg are acceptable for fertile soil [20].

2.5 Soil Phosphate

Phosphorus is one of the major plant nutrients in the soil. It is a constituent of plant cells, essential for cell division and the development of the plant's growing tip [21]. For this reason, it is vital for seedlings and young plants. Without phosphorus, plant growth is retarded. Plants have stunted roots and are checked and spindly. Deficiency symptoms include flat greyish-green leaves, the red pigment in leaf bases, and dying leaves [22]. Phosphorus deficiency is difficult to diagnose, and it may be too late to do anything when it is recognized. If plants are starved of phosphorus as seedlings, they may not recover when phosphorus is applied later—healthy levels of P in soil range from 25 to 50 ppm [23].

2.6 Soil Potassium

One of the essential soil minerals for plants is phosphorus. It contributes to the development of the plant's growing tip and cell division depending on this plant cell component [24]. It is essential for young plants and seedlings because of this. In the absence of phosphorus, plant growth is slowed. Plants are checked and wiry, with stunted roots

[25]. Flat, greyish-green leaves, the red pigment in leaf bases, and decaying leaves are all signs of deficiency. When phosphorus deficiency is discovered, it is too late to act healthy P levels in soil range from 25 to 50 ppm. Therefore, if plants are starved of phosphorus as seedlings, they might not recover when phosphorus is added later [26].

2.7 Soil Salinity

The amount of salts in the groundwater influence osmosis as water enters plant roots. Moisture can return to the soil from plant roots if the salt content of the soil water is too high [27]. The plant becomes dehydrated as a result, which lowers yields or perhaps kills it. Even though the consequences of salinity may not be apparent, crop production losses might nonetheless happen. The capacity of a particular crop to draw water from salinized soils determines how well it can tolerate salt. Because salinity interferes with nitrogen uptake, stunts growth, and prevents plant reproduction, it impacts the production of crops, pastures, and trees [28]. Some ions, most notably chloride, are poisonous to plants, and when their concentration rises, the plant becomes poisoned and perishes. There are about 1600 mS/m of salt per meter where plants can survive [29].

2.8 Soil Carbon

Organic carbon is the term used to describe the carbon found in soil organic matter. An essential element of productive agriculture is soil organic carbon [30]. Numerous soil properties, including stability, enhanced water infiltration, aeration, and nutrient and water holding capacity, are influenced by organic carbon. Microbial activity is crucial for enhancing soil structure because it provides food for soil microbes and is an essential metabolite produced by bacteria. Soil microflora creates macroaggregates by using their secretions to bind soil particles together. These macroaggregates function as the foundation for bettering soil structure [31]. The capacity of the soil to retain water is increased through improved soil structure. For sustainable agriculture, the more carbon stored in the earth, the better. Although SOC can range from 0.3% in desert soils to 14% in intensive dairy soils, dryland agricultural soils typically have an organic carbon content of 0.7% to 4% [32].

3 Recent Advancements on Soil Water Quality Monitoring Systems

Soil water quality monitoring has been the prime component in recent years to ensure a sustainable natural environment while protecting land fertility and water wastage. Numerous research studies have been carried out in the second decade of the twenty-first century towards developing a robust and cost-bearing soil sensing system that can deter accurate water quality parameters inside the soil surface [33,34]. However, conventional soil water monitoring techniques are somewhat laborious and time-consuming, require consistent laboratory instrumentation and are also not feasible when the soil sampling site is far from the testing laboratory. These limitations have been suppressed to a certain extent with the introduction of portable testing techniques such as microwave spectroscopy, remote sensing, and GIS methods without compromising measurement accuracy and instrument sensitivity. This section of the paper intends to review the existing studies conducted towards developing real-time soil monitoring systems with variable cost expenditure and appropriate system accuracy. The reviewed studies are then compared in a tabular form for their testing capabilities and technological drawbacks against our prototype soil sensing system, which is under ongoing design improvement and to be pre-tested for real field deployment.

C. Cojocaru et al. (2020) have used a Teralytic-made commercial three-layered soil probe to gather real-time ground information using the LoRaWAN communication network. The probe measures various parameters at different depths, such as; microclimate parameters like temperature and humidity at surface level, soil parameters including moisture, salinity, temperature, pH, and NPK nutrient monitoring, as well as gas parameters CO2 and O2. The system also features an automated dashboard warning application that ensures real-time alerts for farm users. The major drawback of the study is that it leased already established commercialized soil probes yearly for monitoring soil quality and maximizing crop yields requiring ongoing funding. Real insights are limited to the third-party company, which diminishes its significance in the research domain [35].

Y. Xu et al. (2022) have proposed an experimental investigation on the application of Software Defined Radio (SDR) based wireless soil sensing system by measuring the magnitude and phase responses at discrete frequency levels and applying a Fourier transform to visualize the time-domain reactions to track soil nutrient information. For this, the system utilizes a Surface Acoustic Wave (SAW) device with interdigitated transducers to convert the obtained electrical signal into an acoustic signal and reverse propagation at the output signal to excite the polymer sensor. LimeSDR-mini has been used as a low-frequency carrier to measure in-phase and quadrature (IQ) modulation signals to extract the output. Researchers have also simulated resistance variations of the polymer sensor using the surface mount device resistors on a designed circuit board. Later, the study used RMSE and R-Square analytical techniques to evaluate SDR experimental results with the standard Vector Network Analyzer (VNA) reference values to validate system results and performance. However, the overall experimental setup's signal strength is too weak to analyze, mainly due to smaller gain range settings resulting in clipping and unstable output power [36].

K. Y. Raneesh et al. (2021) have evaluated soil macronutrient detecting sensors and proposed a 3-in-1 prototype sensor gadget to aid farmers in maximizing crop yields by independently measuring on-farm soil NPK, moisture, and temperature. Different soil types (sandy, loam, silty clay, and sandy clay) have been tested for classification and estimating the optimum nutrients and irrigation required for each soil type based on equipped sensor readings in the study. Thereby, soil moisture content and temperature values are determined by measured resistance values in soil. Moreover, the readings from the three-legged instrument are communicated using Wi-fi and can be observed on a mobile application. However, the developed system is a small-scale testing tool that only can measure up to a 1-meter distance in soil and is not a typical representation of the farm field. Moreover, the study hasn’t used data analytics to validate instrument performance and results [37].

B. Kempegowda (2016) have integrated various available soil testing sensors with an ATmega328 microcontroller to develop a real-time soil monitoring system that can contribute to optimal crop production. The multi-sensor prototype system can measure a small area's soil moisture, pH, temperature, humidity, light intensity and carbon dioxide level. In the study, parameter values were captured using LCD for six days and compared against the standardized data to analyze different crop field degradation patterns. Although the study has not integrated any wireless communication protocol for remote monitoring and field implementation, the work done is a scientific contribution to improving agricultural practices [38].

M. Khaydukova et al. (2021) have carried-out traditional physicochemical quantification methods in the laboratory on a range of twenty soil samples extracted from different locations for the quick evaluation of soil macronutrients such as Nitrogen, Phosphorus, Potassium and for estimating quality parameters like pH, conductivity, and organic carbon contents. For this, a compact multisensory system comprising 26 potentiometric sensors was designed for immediate fertility testing in soil-water extracts. A multichannel digital voltmeter with high input impedance is used for sample data collection to determine soil properties. While multivariate regression methods have been implied on the acquired parameter dataset using the Partial Least Square modelling tool for interpreting parameter values and reliability assessment of NPK. The multisensory system was proposed for one-shot simultaneous quantification and estimation of the main soil nutrient parameters that are essential for soil fertility. However, the proposed testing method is performed in a controlled laboratory environment which is time-consuming and laborious, where the multi-sensor system is powered through a laptop and is not representative of actual circumstances. Hence various influencing factors may be contemplated when incorporating actual field deployment [39].

S. Bhaskar et al. (2021) have developed a multi-functional flower harvesting movable robot named as AGROBOT to assist farmers reduce their workload and risks in the field. The system incorporates existing advanced technologies like Image Processing, AI, ML, and IoT and an integrated electronic circuitry mainly comprised on microcontrollers, sensors, and drive motors to perform algorithm-based successive field applications in a farm such as detecting flowers, cutting and placing them into basket, detecting soil moisture, pH, and fertility, detecting pests and spraying the pesticides on plants, detecting the trespassers, and sending real-time alert messages to farm owners. Although, the prototype system has demonstrated ambitious range of farm applications for field farmers but the system has clear drawbacks such as sensor detection readings may not be accurate in many instances creating false alerts as well as incorrect mechanical operations. Moreover, there is a high risk of equipment malfunctioning while performing electro-mechanical operations in uncontrolled farming environment [40].

W. Zhao et al. (2022) carried-out an experimental study by creating different water-stress levels in winter wheat gradient fields to illustrate the importance of having an IoT based intelligent irrigation control system that can determine precise irrigation strategies and regulated treatments based on the physiological indicators and water-stress conditions. The IICS system was developed to monitor real-time soil moisture at different profile layers in the plotted fields and to perform automated irrigation application using PLC controller. The system incorporates Hydra Probe-II as multi-depth soil moisture sensors, MC302L as a low-cost low-power data collector integrated with solar charging controller, po-li battery, gprs/gps, true color touch screen, and other instruments. Furthermore, researchers have performed statistical modelling analysis using ANNOVA and LSD test to evaluate the response of tested indicators. The study concluded that the biomass, yield, and water use efficiency of winter wheat are not much affected in the mild water-stressed fields and are more suitable for irrigation applications than moderate or severe water-stressed fields. However, the limitation of the system is that the findings are limited to the tested crop type and it is not suitable for all soil types, and there is a wastage of fresh water due to the entire area being irrigated multiple times, also the li-po battery is minimal for system application [41].

C. Rusu et al. (2019) have developed a miniaturized real-time soil monitoring sensor to detect soil water content and electrical conductivity. The developed sensor was designed in a lab to use with two set frequency electrodes and a ground to measure electrical impedance of the soil described as resistance and capacitance that are translated into soil conductivity and soil water content, respectively. The soil sensor was tested and calibrated in a potted Jiffy soil media with various known volumetric soil water contents. The microprocessor is also used to digitally communicate the received responses from sensor electrodes via UART interface, while sensor data is read on a pc connected through usb-port also powers the soil sensor. Further, simulation analysis using COMSOL were also performed by the testing researchers to verify the obtained results from the sensor. However, the clear system limitation is that the sensor calibration is only specific to the small area of the tested soil pot with a conductivity range of 0–200 mS m−1, also the researcher has not implemented any network protocol for real-time remote monitoring [42].

S. Millán et al. (2019) have proposed a water-balance algorithm using an automated irrigation control system mainly comprised of soil moisture sensors to automate irrigation scheduling under plum crop field conditions. The device comprises 15 capacitive soil moisture sensors placed at different depths and distances for continuous soil water content measurements. A cloud-hosted interactive web platform IRRIX was used to capture daily parameter data, data processing and analysis, and irrigation applications based on the feedback control algorithm, combining crop water-balance estimations and sensor readings adjustments. Other field equipment includes an air-temperature sensor, datalogger, solar panel with a voltage regulator, lead battery, digital water meter, and a relay controller for solenoid valve application. In the study, researchers have used three irrigation strategies to cover the crop water needs throughout the crop cycle. However, the weaknesses in the system are that it had not considered integrating soil moisture sensors data to determine automated irrigation applications. Also, the monitoring method adopted is not a real-time information system [43].

P. Placidi et al. (2021) have demonstrated the application of self-built IoT-enabled low-cost soil sensing nodes using LoRaWAN network protocol comprised of off-the-shelf components, including sensors, mainly capacitive soil moisture sensors v1.2 and soil temperature sensors. In the study, researchers have compared their obtained experimental results of two types of soils with an already established reference sensor bought from Sentek company to verify the reliability and performance of their sensor node. Measurements of the soil temperature showed good agreement with the referenced sensory system. In contrast, the capacitive soil moisture sensor has shown inconsistency in detecting accurate volumetric water content in the soil. The study has adopted a water infiltration and redistribution modelling approach and has performed statistical analysis to determine the possible correlation between the data values obtained at different depths in the experimented soil types. At the same time, a cloud-based virtual machine server is employed for database management. However, the testing sensors are calibrated in a controlled lab environment for a small bucket scenario and are not conceived for power optimization for long-term, large-scale applications [44]. Table 1 shows the comparative study of the existing groundwater quality monitoring systems.

Table 1: Comparison of recent soil water quality monitoring systems worldwide.

Testing Place	**Sensing tool**	**Measured Parameters**	**Comm. Technology**	**Type of Analytics**	**Weakness**	**Ref.**
Farm field, Romania	Meter long Teralytic soil probe.	moisture, salinity, temperature, pH, and NPK.	LoRaWAN	Summarized dashboard analytics	Leased probe, constant funding, limited data access.	[35]
Lab environment, USA	SAW device as RF detector	Soil nutrient.	LimeSDR-mini as GPR reader	RMSE and R-Square analysis	Weak signal strength, unstable output power	[36]
multiple soil samples, India	3-legged prototype sensor gadget	NPK, moisture, and temperature.	Wi-Fi	Not performed	Small scale measurements, no system validation	[37]
Red soil sample, India	multi-sensor prototype system	soil moisture, pH, temperature, humidity, light intensity and CO_2	Wired LCD	data readings for decision making	No standard calibration, no wireless monitoring	[38]
Lab environment with twenty soil samples, Russia	potentiometric multisensor system	NPK, pH, conductivity, carbon.	Digital mV-meter	PLS regression modelling, reliability test	Powered by laptop	[39]
Farm field, India	Moisture hygrometer, pH	soil moisture, pH, and fertility.	Wi-Fi	Image Processing, AI, and ML	Inaccurate readings, false alerts,	[40]

	sensor, electro chemical sensor				malfunctioning	
wheat gradient field, China	Hydra Probe-II	Soil moisture.	GPRS	Statistical ANNOVA and LSD test	Crop specific, insufficient battery	[41]
Potted Jiffy soil media,	PCB elect. Impedance sensor	Soil moisture, and EC.	Bluetooth	COMSOL simulated FE analysis	Limited calibration range, no remote access	[42]
plum crop field, Spain	10HS capacitance probe	Soil moisture.	Wi-Fi	Water-balance algorithm	No real-time sensor integration	[43]
Small bucket, Italy	Off-the-shelf sensors	Soil moisture, and soil temperature	LoRaWAN (TTN)	Statistical comparative analysis	Inconsistent moisture data, No power optimization	[44]
Residential garden, Australia	Low-cost, low power electrical sensors	Soil moisture, soil temperature, CO_2. tVOC, Amb. Temp, Humidity, Bar.pressure	LoRaWAN	Statistical water balance modeling (to be performed)	Battery optimization and performance validation	Proposed system

4 Proposed System

Our prototype system is a 3D-printed three-layered 600mm long and 50mm broad multi-functional soil sensing node instrument designed to be buried inside the soil in actual farming conditions for measuring soil water content and temperature. Each node layer comprised an anti-corrosive capacitive soil moisture sensor and a digital soil temperature sensor. The multi-functional sensor node also entails CCS811/BME280 environmental-combination sensor that can measure CO_2 (ppm), tVOC (ppb), humidity (g/Kg), temperature (°C), and barometric pressure (kPa). A high-strength digital tipping bucket rain sensor is the centerpiece of the node instrument to determine accurate rainfall patterns.

The real-time wireless sensing system utilizes a low-power, low-cost LoRa transceiver with a center-fed external dipole antenna as a WAN communication protocol for continuous data transmission over considerable distances. In our designed type, the LoRa communication shield is compatible with working on a 915MHz frequency band with a data rate of <50 Kbps at a line-of-site of 10-15 km. The ThingSpeak cloud server

is used as an IoT analytics platform to visualize and analyze the live data streams of the developed sensor node. Other main components of the prototype system include; the Arduino Mega 2560 microcontroller, which is the heart of the system that has 54 digital i/o's, 16 analogue inputs, a Stackable 6V 6W solar charger shield with environmentally friendly 3.7 V 6000 mAh rechargeable polymer lithium-ion battery used for adaptive power consumption and energy harvesting in the field environment, Qwiic shield to enable I2C bus on Arduino MCU in series to connect the environmental combination sensor. Fig.2 shows the connection diagram of the proposed system.
The electronic shields are glued and enclosed inside an electrical junction box to be used as a protective mounting device. The box enclosure is screwed properly and sealed with silicon epoxy coating to make the hardware design more water resistant, UV protective, and environmentally safe. For outdoor field installation, the system hardware is being designed to be deployed on a pointed metal fence post using pole mounting brackets to ensure a firm and robust hardware installation that can withstand harsh weather conditions.

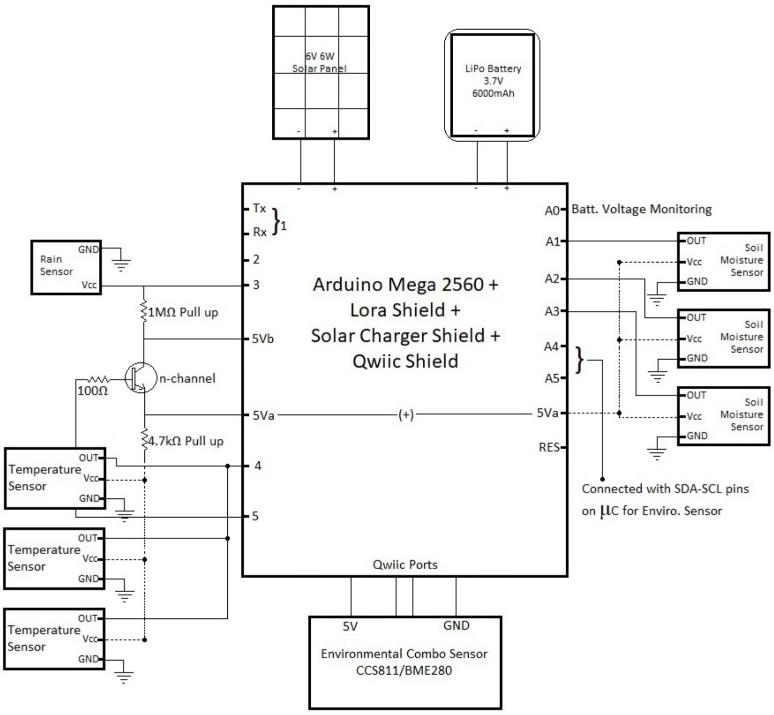


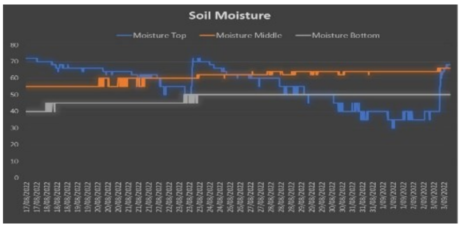
Fig.2. Connection diagram of the proposed system.

At this study stage, the prototype system is under ongoing hardware design improvements, code development, and potential functional enhancements to accomplish long-term, large-scale application capability. The initially developed system was deployed in a residential garden for twenty days to perform preliminary testing and statistical analysis and to identify technical challenges encountered during remote installation.

4.1 Field Installation and Preliminary Results

The initially developed two soil sensing nodes were first experimented in the lab for electronic circuit testing, calibration, and reference value measurements before being deployed in a real field for obtaining experimental data in outside uncontrolled environment. Below Fig. 3 shows the installation of first two sensor probes at a residential garden. The installation time was more than two hours for two instruments. The main tool used for digging a 600mm deep and 50mm wide hole in the soil was a heavy-duty steel Giantz Power Augur which is compatible with most of power drills along with other necessary equipment available onsite.

Fig. 3. Installation of two sensor nodes at a residential garden for pre-testing



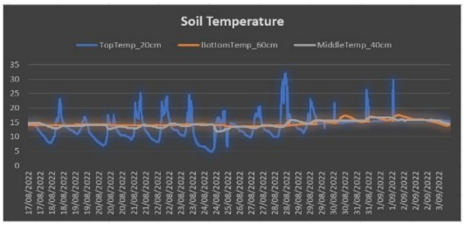
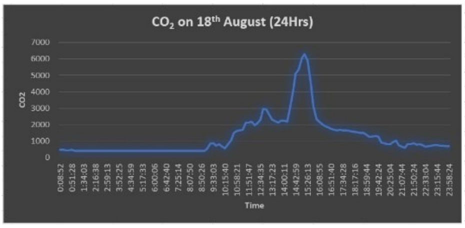


Fig. 4. Three-layered Soil moisture readings. **Fig. 5.** Three-layered Soil temperature readings.



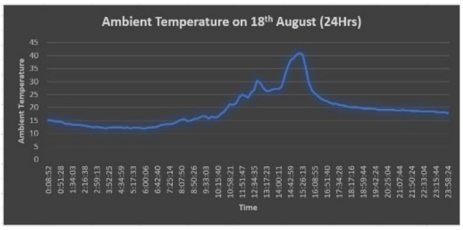


Fig.6. Carbon dioxide emission during 24hrs. **Fig.7.** Ambient temperature during 24 hrs.

Figure 4 shows the readings of the volumetric water content data obtained from the capacitive soil moisture sensors at three different depths of the soil that is top (20cm), middle (40cm), and bottom (60cm). As can be seen the top layer of the surface shows more variations in moisture readings than the second and third layer of the probe due to mostly exposed to direct rainfall, sunlight, and other climatic conditions. Since moisture data is inversely proportional to the capacitive sensor readings. Thereby, on seventh and last day of the testing we had a good rain precipitation onsite which is translated into higher water content data on those days at the top layer of the surface from 48% to 72% and 40% to 68% of moisture readings. However, the middle and bottom layer sensors being less exposed to direct rainwater and sunlight show unfluctuated steadily declining readings maintained throughout the testing period which can be translated as middle layer being moderately moistured from 55% to 66% while the bottom layer is interpreted as close to a less moistured surface from 40% to 50% moisture readings.

Alongside, figure 5 shows the temperature readings from the digital soil temperature sensor along with the moisture sensor at three subsequent layers of study surface. In parallel with the top soil moisture sensor, the soil temperature sensor at the top layer also shows periodic variations in temperature readings from 5°C to 30°C due to first point of contact to rainwater and to daylight heat. However, the middle and bottom soil temperature sensors exhibit constant readings 15°C maintained at 40cm and 60cm depth inside soil throughout this period.

Figure 6 shows the carbon dioxide CO_2 (ppm) concentration present in air over a full-day period acquired from the environmental sensor CCS881 used in the system. As can be seen the carbon dioxide in air remained unchanged during the night till 8:50am and has increased with fluctuations from 9am to 2pm from 400ppm to 2200ppm. After that, it has a further rapid increase from 2200ppm to 6200ppm during 2-3pm while a quick drop in volume to 2200ppm again in the next hour perhaps due to the increase in gas emissions by vehicles passing through the site. In the last 8 hours till midnight, the CO_2 concentration continued to decrease gradually from 2200ppm to 400ppm. On the other hand, figure 7 presents the ambient temperature readings acquired from the environmental sensor BME280 over a full-day period. The ambient temperature seems to have higher values during day time reaches up to 40°C while it exhibits lower values 15°C amid night.

5 Conclusion and Future Works

All the critical parameters of groundwater and their impact on soil quality have been successfully demonstrated. Moreover, the optimum level of each factor to ensure healthy soil for sustainable agriculture has also been discussed. Additionally, technologies existing for soil quality monitoring systems have been discussed and compared. Furthermore, a self-contained intelligent soil sensor node has been proposed to monitor the condition of the soil and groundwater. The main benefits of using the proposed system compared to existing systems are incorporating inexpensive, low-power sensors and optimisation of wake-up time to increase the lifetime of the sensor node. The proposed system's implementation fee of USD 300 includes the cost of buying a few electronic components. The overall cost can significantly decrease if the product is produced in larger quantities. Having said that, the current IoT based project has significant future plans to implement in the proposed system. At the moment, the current soil sensor node is undergoing significant design and functional improvements for optimizing system longevity and results accuracy. Also, the fabrication of a soil quality detection sensor and its integration in a microcontroller-based IoT system is under investigation to be included in the system in near future. Moreover, with the help of real-time data analytics and evapotranspiration modeling, the system will be more capable of predicting accurate climatic conditions and profitable agricultural decision making. Owing to the fact, the expected outcomes of the project can be successfully achieved with distinctive quality and in minimum study period if it can attract substantial industry collaboration and commercialization. On the whole, the systems suggested in the study fulfil agriculture 4.0 goals, not only applying pesticides but also managing the farms using cutting-edge technology, such as sensors, machinery, gadgets, and IoT based communication. Any agricultural farm using these systems will be able to use modern technologies efficiently to make more profitable and productive decisions in the future.

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