International Journal on Advanced Science Engineering Information Technology

Vol.13 (2023) No. 4
ISSN: 2088-5334

Optimization of Soil Temperature and Humidity Measurement System at Climatology Stations with IoT-Based Equipment

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Abstract*— Temperature and humidity are important weather parameters that require close observation due to their importance across various fields, including agriculture. Apart from using automatic weather system (AWS), the station of meteorology and climatology also relies on conventional devices to observe these parameters, but they have been proven inefficient, imprecise, and prone to systematic errors. The alternative AWS consists of several sensors with different functions, allowing for more accurate measurements, but it also has one major limitation. This includes its inability to carry out measurements with the sensors when one of them is damaged. Therefore, this study aims to develop high-precision soil temperature and humidity (STH) monitoring equipment using the DHT11 sensor module. The equipment consisted of a box containing a series of device builder electronics. The building electronics circuit contained a DHT11 sensor, NodeMCU ESP8266 microcontroller, an on/off switch, and a reset button. IoT and cloud databases have also been incorporated into the system. The results of measurements of temperature and humidity often appear on the smartphone. The DHT11 sensor detected the soil parameters, which the NodeMCU ESP8266 processed. The data obtained were then sent to Thingspeak, where they could be accessed on a smartphone. The developed equipment showed good performance with accuracies of 98.201%, 97.330%, 98.982%, 98.973%, and 99.649% in measuring STH at each depth, while values of 98.487% and 98.587% were obtained for humidity measurement. Furthermore, 99.93% and 99.95 precision values were recorded to measure temperature and humidity.

***Keywords*— DHT 11; temperature; humidity; soil; IoT.**

Manuscript received 5 Apr. 2023; revised 2 Jun. 2023; accepted 17 Aug. 2023. Date of publication 31 Aug. 2023.

I. INTRODUCTION

Soil temperature and humidity (STH) are essential weather parameters [1]–[5] needed across various fields, such as agriculture, indicating that they must be monitored carefully. Soil temperature and humidity are significant in water resource management, such as early drought warning and irrigation scheduling. Overall radiation, a mixture of wavelength emissions from heat transport in the soil, determines soil temperature. The mechanisms of nutrient absorption by roots, photosynthesis, and respiration are all affected by soil temperature. Soil humidity is a water source for the atmosphere via mechanisms leading to evapotranspiration from land, including plant transpiration and bare soil evaporation. [6]–[8].

In agriculture, soil quality is an influential aspect of the plant-growing process, which needs to be maintained for proper growth [9], [10]. Furthermore, the selection of plant species for a particular area is closely related to the temperature and humidity of the growing media [11], [12]. This indicates that farmers must carefully consider these parameters to produce high-quality product varieties, as they are required for determining appropriate treatments and interventions. Based on previous reports, global warming has caused significant fluctuations and extreme temperature changes, making it difficult to predict seasonal changes [13], [14]. In the last decade, the seasons can be anticipated by counting the months of each year, but recent climate anomalies are unpredictable, making it difficult to determine their impact. This uncertainty has impacted all sectors of life, with agriculture being the most affected [15]. A decline in soil quality and fruitfulness has been reported to have the ability to decrease agricultural productivity [16] and increase crop failure. Therefore, it is important to implement a rigorous monitoring system for STH to maintain optimal conditions.

Apart from the automatic weather system (AWS), the station of meteorology and climatology also uses conventional equipment, including a mercury thermometer, to measure STH parameters [17], [18]. Several thermometers are placed in different areas at varying depths to take measurements, but this method is inefficient due to the difference in soil structure. This indicates that conventional equipment is inefficient in measurement procedures, lacks precision, and is prone to systematic errors. During the reading of the measurement result, a thermometer needs to be lifted from the hole with some depth, leading to transient phenomena and high error. The station of meteorology and climatology often uses a digital soil humidity device to measure the humidity level, but it is limited to a depth of 20 cm.

Meanwhile, AWS consists of several sensors with various functions to measure different parameters, and it has also been reported to have some limitations, including a complicated electronic circuit, expensive spare parts, and high power consumption [19]. The display of AWS is typically located on a PC, which presents a limitation in terms of mobility. Moving the device from one site to another is challenging, as STH can vary across various areas.

Several temperatures and soil humidity have been developed using various techniques, including an IoT-based agriculture system incorporating an LM35 temperature sensor and a VL95 soil sensor controlled by an Arduino microcontroller or NodeMCU ESP8266 [20]. However, this system requires users to visit the thing-speak platform to assess the data collected manually. Another application that allows real-time temperature measurement and parameters has been developed using LM35, DHT11, and soil humidity sensors, but it is limited to a depth of 5 cm [21]. Other detection systems utilize a DHT22 sensor to measure air temperature with the display through LCD [22]–[24]. A water and soil quality monitoring system has also been integrated with a Wi-Fi module for agricultural greenhouse fields [25]. The system has also incorporated sensor reading, IoT, and cloud databases.

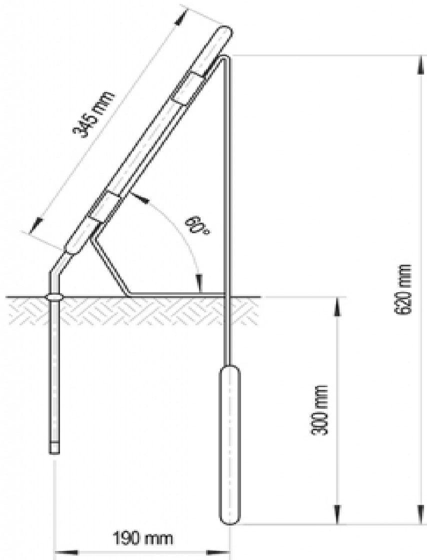
This system uses a DHT11 sensor and transfers data to a Cloud server for remote access using an Arduino microcontroller at regular intervals through the ESP8266 Wi-Fi module [26]. A temperature and soil humidity monitoring system has also been developed using an SHT11 sensor for both Arduino microcontroller and NodeMCU ESP8266, with data storage in micro SD memory [27]. However, the use of micro-SD poses a risk of data loss or damage due to malfunction. Another device used for measurement was developed with a humidity and temperature sensor mounted on the project board Wi-Fi module, but it could only be used on the surface of the soil [28].

This study developed an automatic high-precision STH measuring device using five pieces of DHT11 sensor and a NodeMCU microcontroller. STH is portable and consists of 5 channel DHT11 placed at 5 different depths. Due to the use of 5 different channels at different soil levels, measurements can be made at various depths simultaneously. STH device is IoT-enabled, and the data obtained can be accessed from the Thingspeak Cloud storage website on an Android-based smartphone. The device can detect up to 100 cm of soil depth with high precision and is applicable in the station of meteorology and climatology for STH monitoring. STH has affordable components, indicating that farmers can use it to take measurements.

II. Materials and Methods

Direct observations were first made at the climatology station to gain insight into the functionality of the conventional tools. The measurement instrument used in this study contained a thermometer, which was implanted into the soil to a predetermined depth based on WMO (World Meteorological Organization) rules.

(a)



(b)

Fig. 1 (a) The conventional measurement system used at the climatology station. (b) Thermometer sketch (https://www.th-friedrichs.de/)

Conventional measurements are taken at climatological stations using adapted mercury thermometers at each depth. Thermometers are arranged in rows according to their depths, which are 5 cm, 10 cm, 20 cm, 50 cm, and 100 cm, in accordance with WMO norms. The measurement times used by the climatology station are 07.30 WIB, 12.30 WIB, and 17.30 WIB. The weakness of this system is that manual data collection is carried out directly into the field, with scale readings that have the potential to cause parallax errors, and in soil temperature measurements at a depth of 50 cm and 100 cm, the thermometer is lifted up to take readings, which can cause measurement errors due to the influence of depth temperature lifted to the ground surface. Based on the results of direct observations, an automatic measuring tool was designed, which utilized sensor, IoT, and cloud database technology to facilitate measurement.

Furthermore, the data obtained from the measurement could be read and visualized through a smartphone. STH system was developed using the 5 pieces of the DHT11 sensor module controlled by the NodeMCU ESP8266 microcontroller. The 5 pieces of DHT sensor were implanted at 5 different soil depths of 5 cm, 10 cm, 20 cm, 50 cm, and 100 cm. STH was IoT-enabled and connected with a smartphone-based Android operating system through NodeMCU ESP8266 and MIT App Inventor [29], which allowed for display through the smartphone. The NodeMCU ESP8266 was used to transmit data to the web server in Android-based smartphones. The Real-time data collected were saved in the web server of Thingspeak Cloud Storage [30], which allowed for easy accessibility, and Data from thing speak is easily accessible and exportation of data in multiple formats. The diagram block of the equipment hardware system is presented in Fig. 1. DHT11 consisted of a single relative humidity chip and a multi-temperature sensor with digital output. The sensor output obtained 40 bits of data for temperature and humidity measurement, requiring no signal conditioner or ADC [31]–[33].

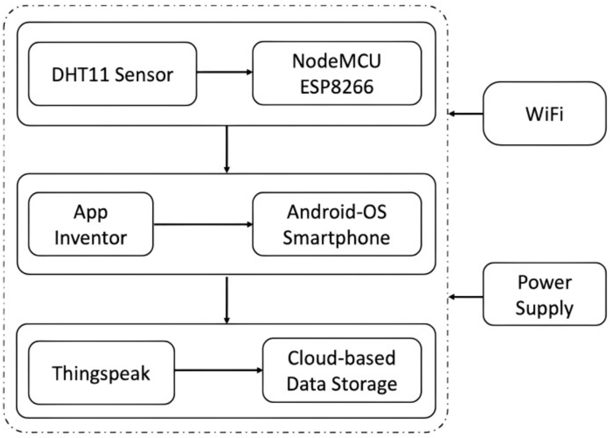


Fig. 2 Diagram Block of STH System

The DHT11 sensor module consisted of a resistive and NTC temperature gauge, where the resistance was inversely proportional to the temperature. Furthermore, the capacitive humidity sensor embedded in the DHT11 sensor module contained two detecting electrodes, and its capacitance changed with humidity. It also consisted of a reference and feedback capacitor with a metallic electrode sandwiched between them and a humidity-sensitive polymer layer. The capacitive humidity sensor had excellent performance, fast response, anti-interference capability, and high-cost advantage of qualities and performance [34].

Fig. 3 shows the schematic diagram of the electronic circuit of STH system. The components of the electronic circuit were placed in a black box. The components used consisted of a 9 Volt power adapter, 5 units of DHT 11 sensors, a NodeMCU ESP8266 microcontroller, a switch, and a reset push button.

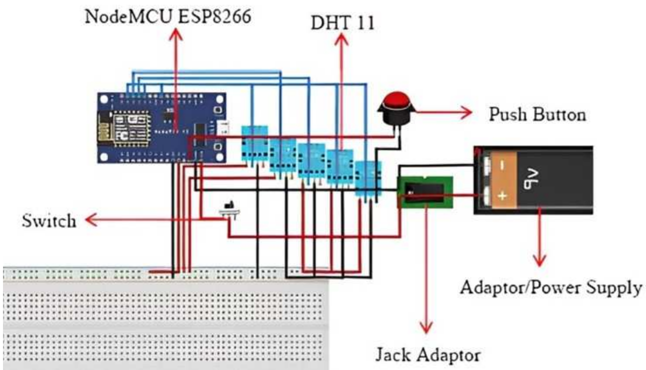


Fig. 3 The Schematic Diagram of STH Electronic Circuit

Furthermore, the equipment was activated run when the switch button was turned on. STH data were recorded and then displayed in a web server of Android-based smartphones through NodeMCU ESP8266 microcontroller [35]–[37]. The programming flowchart is presented in Fig. 4.

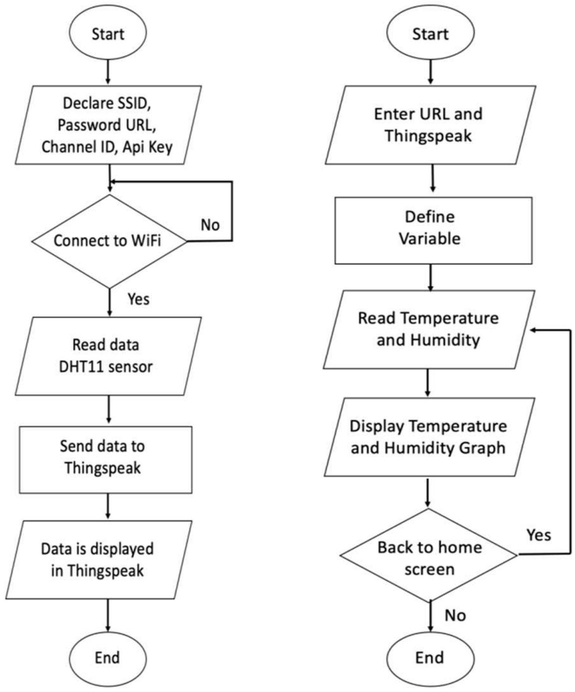


Fig. 4 Flowchart of microcontroller and MIT App inventor

Based on Fig. 4, the programming script for NodeMCU ESP8266 was compiled using Arduino IDE with a C++ programming language [38], [39]. The important component added to the programming script was the process of sensor data transmission to the web server Thing-speak, as shown in the flowchart. Data transmission required Wi-Fi to connect the NodeMCU ESP8266 microcontroller to the Thingspeak [40], [41]. In the event that a Wi-Fi connection was not found, STH often attempted to reconnect and find an available internet connection. The interface and data display on the Android-based smartphones the MIT App inventor programmed were adjusted to the flowchart [42], [43]. The feature that could be accessed on this interface was the data of STH parameters and the graph of the measurement results in real-time.

STH consisted of a 5-piece DHT sensor, which was placed in different depths of soil, as shown in Fig. 5. These 5 channels of temperature and humidity detection system had the ability to monitor the temperature and humidity changes in soil up to 100 cm at the same time in real time. Grassland and barren land were measured in this study to compare the difference in these parameters for the two kinds of soil structure.

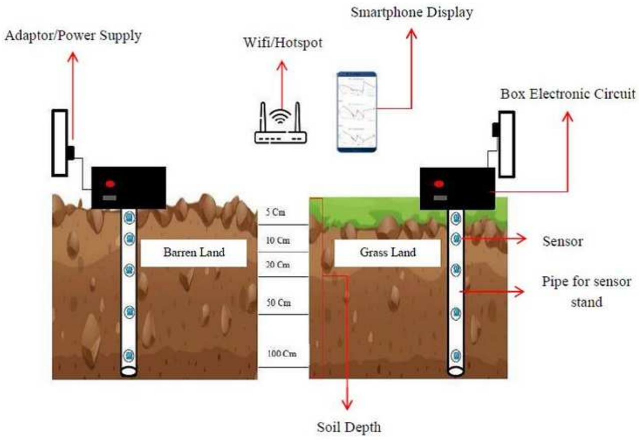


Fig. 5 Measurement Setup

The schematic of the measurement setup is presented in Fig. 5. A 120 cm pipe was used to place sensors at different depths, and the electronic circuit black box was positioned at the surface of the soil. The outer side of the black box had a restart push button, which could be used to activate STH system. All the data collected were compared with the soil mercury temperature and humidity sensor available in the station of meteorology and climatology to assess the precision and accuracy of the developed STH system.

III. Results and Discussion

A. Hardware System

All components were placed in the thick and waterproof black box to meet the criteria of long-term usage of electronic system, as shown in Fig. 6. The main features, such as the microcontroller, push button, switch, and the entire wiring of the sensor were also arranged. Furthermore, the box was connected directly with a pipe designed to be a 5-unit DHT 11 sensor stand at a predetermined depth for measurement of STH. The power source used was a 9 Volt adapter, which supplied current. The tool was also equipped with a hotspot to support the IoT system, which was used to send data directly to the web server. The display used was an Android smartphone to facilitate the data retrieval process as well as increase its efficiency. Fig. 6a shows the electronic circuit in the black box, while Fig. 6b illustrates the hardware system.

The system was composed of a series of components and a simple electronic circuit designed with maximum function. The main part of the hardware was the waterproof box containing the constituent components as well as a 120 cm pipe that was used to mount the 5 pieces of DHT 11 sensors.

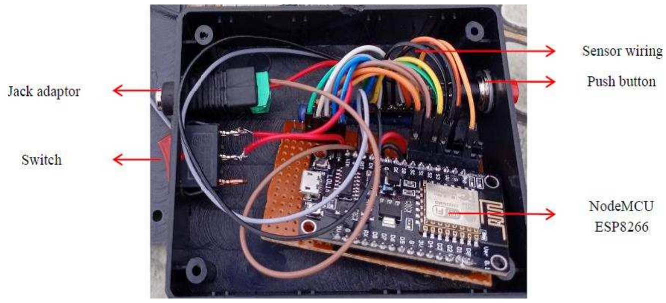


Fig. 6a Electronic Circuit

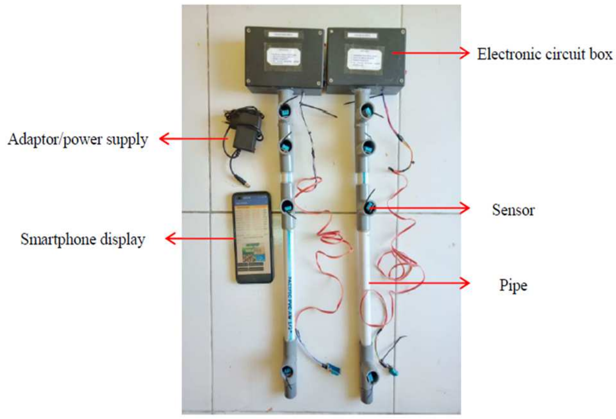


Fig. 6b Hardware System

B. Software System

The data read by the sensor will be sent to the webserver Thingspeak using a Wi-Fi network with the help of a NodeMCU microcontroller. The Thingspeak webserver also acts as a database for all incoming data from sensors and can be visualized as real-time graphs. Any data that enters the Thingspeak webserver can be exported in CSV format for further analysis. The following can be seen in Figure 7 for the reading system on the Thingspeak webserver:

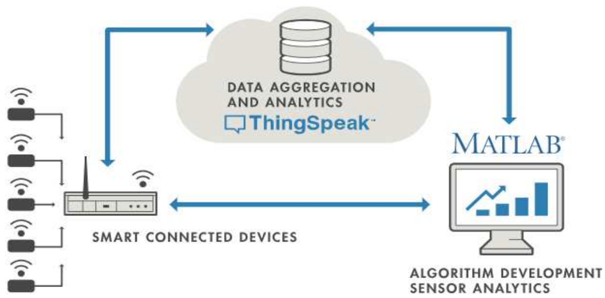


Fig. 7 Data reading system on ThingSpeak webserver

The software of Arduino IDE was used to code the algorithm, as shown in Fig. 4. Furthermore, the program was designed and uploaded to the microcontroller. After the microcontroller program was designed, the system sent data read by the sensor to the web server Thingspeak. To display data on a smartphone, the MIT App Inventor was used to design a mobile application that could retrieve data sent to a web server Thingspeak, as shown in Fig. 8.

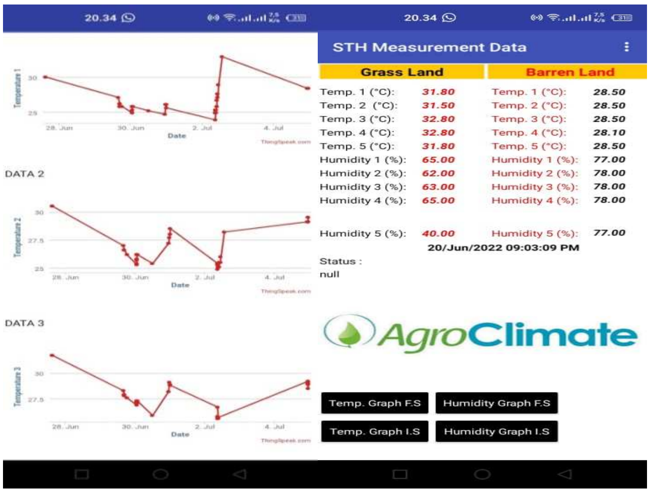


Fig. 8 Screenshot of on Android smartphone

The real-time running time, soil temperature values, soil humidity values, and a button to enter a page containing graphs were displayed on the Android Smartphone. When the application was launched, a display appeared in the form of sensor data on two types of soil, namely grassland and barren land. Data were sorted in each column by measuring 2 parameters, namely temperature and humidity. The application also had a real-time time recording feature in the form of the month and year dates with the current time. The button feature was used to direct the user to a real-time monitoring chart display with automatic time recording. Recorded data were stored in a web server database with historical data that could be converted to various formats.

C. Validity Test for the Accuracy

A validity test was used to determine the accuracy and precision of the measuring instruments. The validity of the accuracy was tested by comparing the value generated by the sensor to those obtained from the conventional tool in the form of a soil thermometer used by the climatology station. The display of the DHT 11 sensor was a calibrated digital output with an error tolerance of 2°C and 5% for temperature and humidity, respectively. In the validation test, the sensor's response to the thermometer, which was mounted on its side was assessed to determine the accuracy. The results of the sensor’s accuracy were indicated by the linear regression values obtained, as shown in Fig. 9. The evolution graph was used to compare the performance of the DHT 11 sensor to the standard climatology station soil thermometer and humidity.

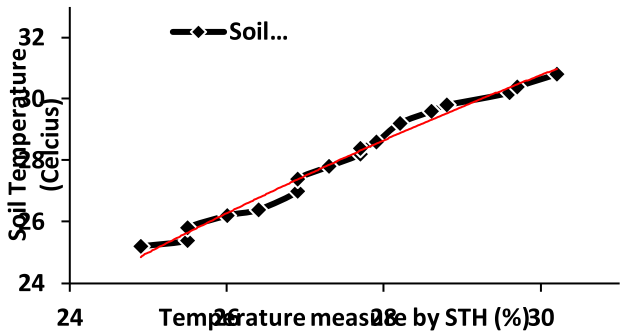


Fig. 9a Graph of the characterization of the DHT 11 sensor on soil temperature measurements

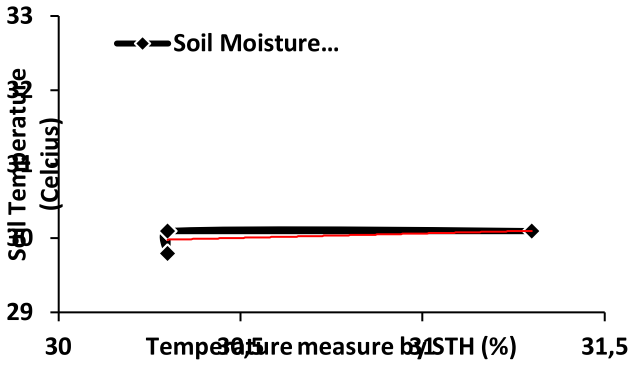
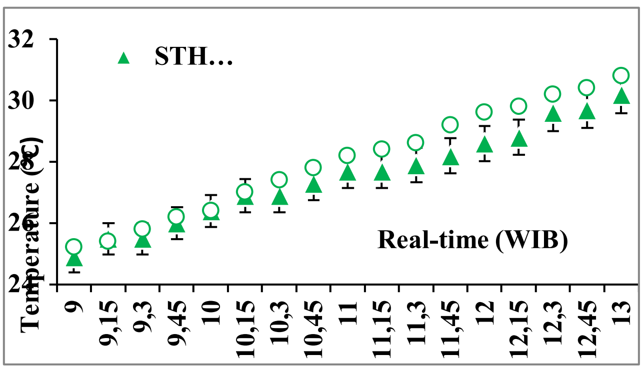


Fig. 9b Graph of the characterization of the DHT 11 sensor on soil humidity measurements

Based on Fig. 9, the characterization value of each parameter was tested by taking direct measurements at the climatology station. Fig. 9a shows the characterization level of the DHT 11 temperature parameter with a soil thermometer. Furthermore, a very good level of accuracy was obtained with an R-square value of 0.9825 and an average error percentage of 1.8 %. Data measured using SHT were overlapped with those recorded from the conventional tools. The results showed that the data from STH was close to the actual readings. Fig. 9b shows the level of characterization of the DHT 11 humidity parameter with soil humidity. The R-square value obtained was relatively low because the measurement of soil humidity was fairly constant and there was no fluctuating data. Based on these findings, the independent variables' ability to explain the dependent variable was limited. The STH had an error percentage of 1.41% while measuring low soil humidity levels.

The measuring instrument data were collected simultaneously with those of the standard measuring instruments from the Climatology Station. The measurements were carried out for 4 hours with data collection once every 15 minutes in two different conditions, and there were 5 depths, namely 5 cm, 10 cm, 20 cm, 50 cm, and 100 cm. On July 2nd at 09.00-13.00 WIB, the data obtained from the measuring instrument were compared with the standards at the Climatology Station, namely soil thermometers. Furthermore, this comparison was performed to determine the sensor's response to temperature increases from morning to noon. The measurement data could be used to assess the sensor's accuracy on each pattern of temperature changes from morning to noon within 4 hours, as shown in Figs. 10 and 11.



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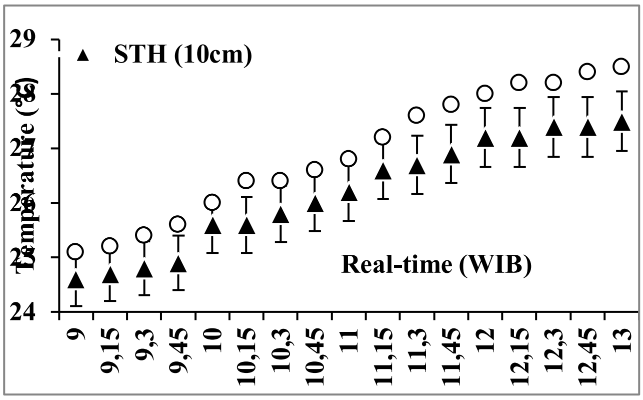

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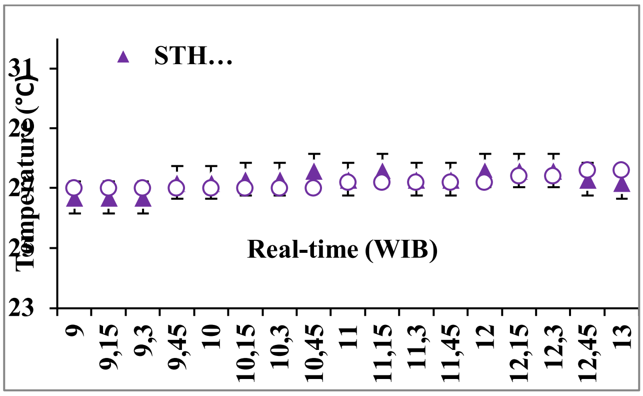

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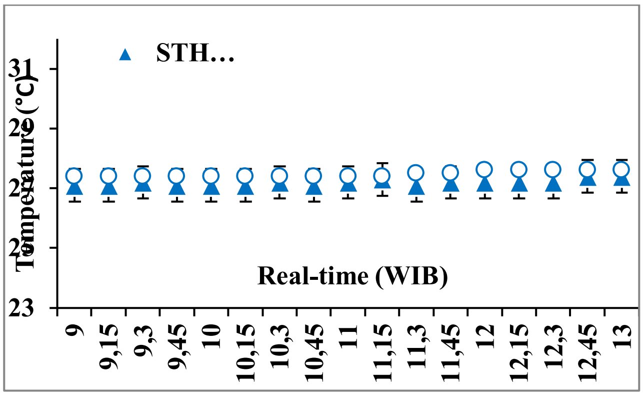

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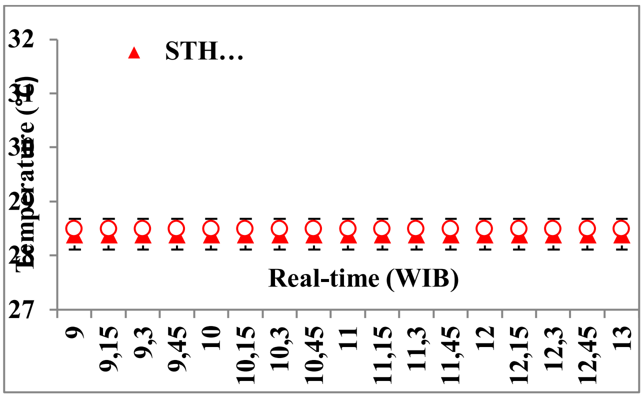
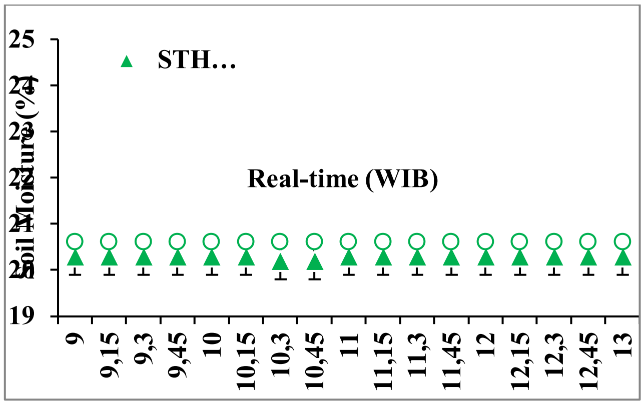


(e)

Fig. 10 Data Accuracy for STH temperature

Fig. 10 shows that the measurement for 4 hours from morning to noon was carried out to determine the sensor's response to changes in heat on the ground caused by the high solar radiation during the day. The movement of data in the 4-hour measurement range fluctuated with surface depth due to the proximity of the surface to sunlight exposure. The fluctuation data were observed at a depth of 5 cm, 10 cm, and 20 cm.

At a depth of 50 cm and 100 cm, the data became constant due to the wide distance from the reach of direct solar radiation propagation, which delayed heat transfer. Therefore, the highest temperature was obtained at 50 cm and 100 cm during the night, as the areas stored heat from the sun. The results showed that the equipment had a good performance in measuring soil temperature with accuracies of 98.201%, 97.330%, 98.982%, 98.973%, and 99.649%. The accuracy of the measuring tool for soil humidity was determined by taking measurements at depths of 10 cm and 20 cm, and the results were compared to standard values from the climatology station. The graph of the sensor response to measurements at each depth within 4 hours is presented in Fig. 11.



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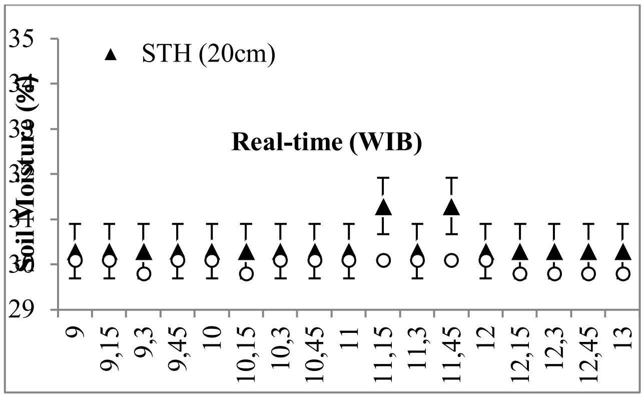


(b)

Fig. 11 Data Accuracy for STH humidity

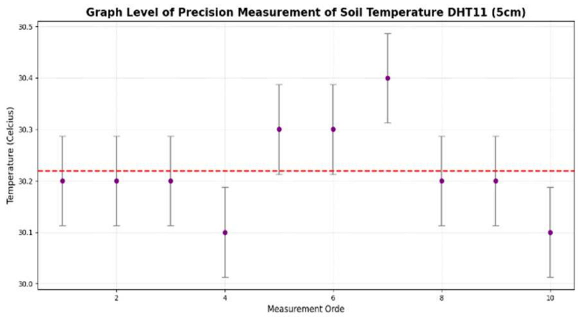
The measurement for 4 hours from morning to noon obtained constant data for humidity because evaporation activity at this depth range was delayed, as shown in Fig. 10. The results also showed that some data had relatively high deviations because the standard tools used by the climatology station were not permanently embedded in the ground. Consequently, the humidity probe must be removed while collecting data on other types of soil, leading to inconsistencies in the standard tools. The accuracy of measuring soil humidity at each depth was 98.487% and 98.587%

The measurement results obtained accurate data on STH using the measuring instruments. Several sources on the importance of temperature and humidity for plant growth were added to this study to support these findings. These parameters were elements that affected the development of plants. The results showed that the temperature recorded during the day and at night differed. During the day when the soil surface was illuminated by sunlight, the air close to the ground surface received high temperature, but the value often decreased at night soil temperature. Soil temperature had been reported to have an effect on water absorption, where the lower its value, the lesser the water absorbed by the roots. This explained the reason for the sudden drop in soil temperature, which led to wilting of plants.

The deeper the soil, the slower its ability to absorb and spread sunlight, leading to lower temperature. Furthermore, the higher the temperature, the faster the ripening of plants. The main influence of soil temperature on plants was on seed germination, microbial activity, and development of diseases, root activity, as well as plant growth acceleration and duration. Soil humidity played a role in several government initiatives, such as identifying soil erosion failure, assessing the potential for runoff and flood, managing water resources, as well as determining slope, geotechnical, and water quality. Factors affecting soil humidity included rainfall, soil type, and evapotranspiration rate. Soil humidity had been shown to determine the availability of water in the soil for plant growth.

D. Validity Test for the Precision

For the level of precision, repeated measurements were carried out 10 times for each parameter under the same conditions, as shown in Figs. 12 and 13.



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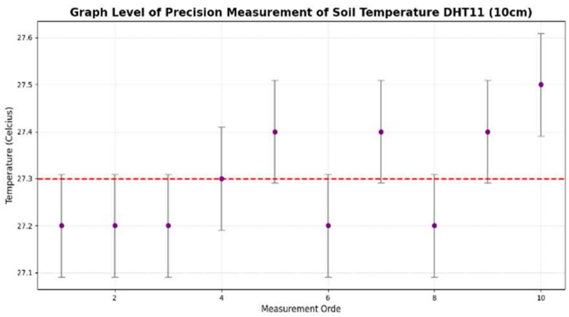

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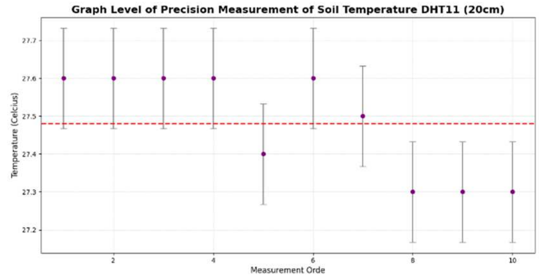

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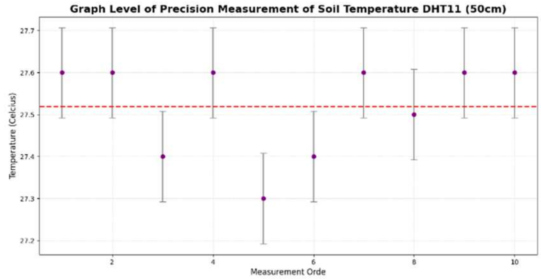

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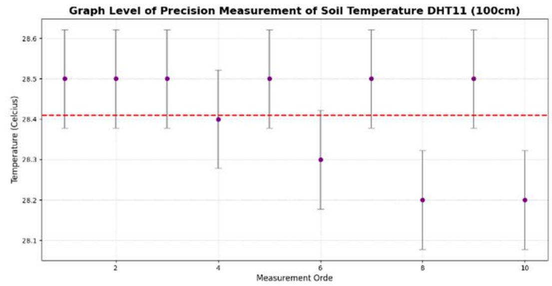
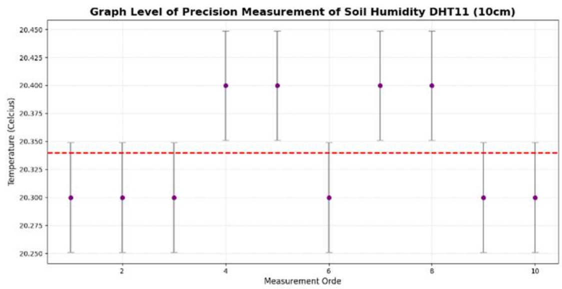


(e)

Fig. 12 Data Precision for STH Temperature

The sensor used in measuring temperature parameters had an average precision of 99.93%. Furthermore, the precision data on humidity parameters measured by the DHT 11 sensor is presented in Fig. 13.



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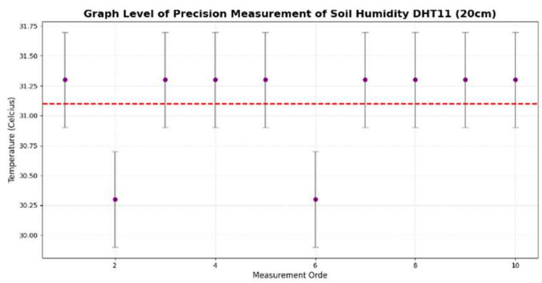

(b)

Fig. 13 Data Precision for STH humidity

The measurement precision of the soil humidity parameter was determined through 10 repetitions at depths of 10 cm and 20 cm. From the results of data measurements at the two depths, an average precision of 99.95% was obtained.

IV. Conclusion

STH measuring instrument consisted of a box containing a series of electronic devices. Furthermore, the electronic circuit of the instrument contained a DHT11 sensor, NodeMCU ESP8266 microcontroller, an on/off switch, and a reset button. The results of the measurement of temperature and humidity were presented and viewed on a smartphone. The DHT11 sensor had the ability to detect the temperature and humidity of the air, which the NodeMCU ESP8266 then processed. The data obtained were often sent to the Thingspeak server, where they could be accessed on a smartphone. Data is automatically stored in the cloud database system on Thingspeak and can be exported in CSV format. The average accuracy of measuring STH at each depth was 98.201%, 97.330%, 98.982%, 98.973%, and 99.649%, while values of 98.487% and 98.587% were obtained for soil humidity. The instrument's precision in measuring temperature and humidity was 99.93% and 99.95%.

Acknowledgment

This study was supported by Universitas Negeri Padang with Contract No: 991/UN35.13/LT/2022.

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