Comparative Performance of Four Soil Moisture Sensors in Arid Conditions: Low-Cost and Commercial Options

Onan Agaba[1], Mulugeta Weldegebriel Hagos[1], Fatima-Zahra Kasmi[2], and Elad Levintal[2*]

[1]French Associates Institute for Agriculture and Biotechnology of Drylands, [2]Zuckerberg Institute for Water Research, Jacob Blaustein Institutes for Desert Research, Ben-Gurion University of the Negev, Sde Boqer Campus, 84990, Israel

1. Introduction

Soil volumetric water content (θ_v) is an important parameter used to understand various environmental and ecohydrological processes. Accurate measurements of θ_v are essential for data-driven sustainable agriculture, particularly in optimizing irrigation practices (Adla et al., 2020). Traditionally, the gravimetric method has been considered the most accurate approach for measuring θ_v (Gardner, 1986). However, this method is labor-intensive, time-consuming, and destructive (Kargas & Soulis, 2012). Consequently, this has led to the development of various indirect and non-destructive methods (Bogena et al., 2017; Hubner et al., 2009). Such methods include time domain reflectometry (TDR) (Robinson et al., 2003), electrical capacitance (Kojima et al., 2016), neutron thermalization (Greacen, 1981), impedance sensors (Gaskin & Miller, 1996), and time domain transmission (TDT) (Blonquist Jr et al., 2005).

Among these methods, electromagnetic-based sensors such as TDR, TDT, frequency domain reflectometry (FDR), and capacitance sensors have gained popularity. TDR and TDT operate on the principle that electromagnetic waves travel through the soil at different speeds based on water content, since water has a much higher dielectric permittivity (of approximately 80) compared to air (around 1) and dry soil (between 3 and 7) (Abdelmoneim et al., 2025; Adla et al., 2020; Bogena et al., 2017). Additionally, they operate at high frequencies (in the GHz range), where θ_v measurements are less affected by the electrical conductivity (EC) of the soil (Blonquist Jr et al., 2005). However, TDR sensors require complex waveform analysis and are usually limited by their high cost (Kargas & Soulis, 2012).

To overcome these limitations, more cost-effective alternatives such as FDR and capacitance sensors operating in the 50-150 MHz range have been developed (Seyfried & Murdock, 2004). FDR estimates soil moisture by analysing the response of an oscillating electrical signal to the soil's dielectric constant, while capacitance sensors measure the time required to charge a capacitor using soil as the dielectric medium (Gümüser et al., 2025). Furthermore, FDR and capacitance sensors provide similar advantages in terms of applicability across various soil types, easy to use, and suitability for continuous monitoring (Dean et al., 1987). The cost of commercially available θ_v sensors spans over four orders of magnitude (Adla et al., 2020), which has driven increasing interest in low-cost alternatives. This trend is evident in the growing number of peer-reviewed publications on low-cost moisture sensors over the past four decades (see **Error! Reference source not found.**).

Despite this rising interest, low-cost sensors face significant challenges, such as sensor-to-sensor variability (Rosenbaum et al., 2011), which can compromise measurement accuracy if not properly addressed (Bogena et al., 2017). To assess the viability of low-cost options, this study categorizes sensors into two groups: 'low-cost' sensors, defined by their affordability, and a 'commercial' sensor, represented by a high-end unit serving as the reference standard. Based on this classification, we selected three low-cost sensors and one TDR-based commercial sensor (see Table 1). Our objective is to evaluate the performance of the low-cost sensors by comparing their θ_v measurement accuracy to that of the commercial TDR sensor.

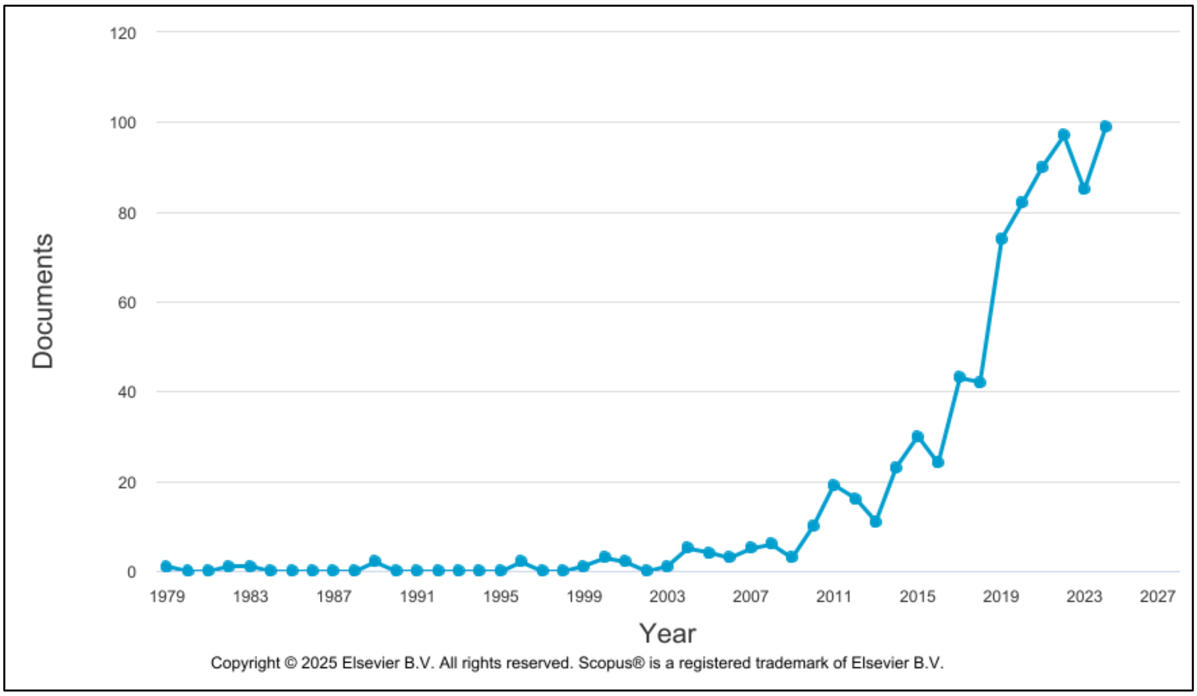

Figure 1: Increasing trend of peer-reviewed publications on low-cost soil moisture sensing

2. Materials and Methods

2.1 Hardware

Hardware used to develop the soil moisture logging system included a microcontroller, real-time clock (RTC), a lithium battery, voltage dividers, boosters, and soil moisture sensors (see Figure 2 and **Error! Reference source not found.**). The Adafruit Feather M0 Adalogger was u sed as the microcontroller. It includes built-in features ideal for logging applications, such as multiple peripheral pins, a lithium polymer battery connector, a micro-SD card slot, and a micro-USB port for programming (Fahlbusch & Harrington, 2019). These features allowed us to connect all sensors and customize the board into a data logger. The system was powered by a lithium battery, and voltage boosters of 5 and 12 V were incorporated to step up the voltage for the DFRobot and TDR-305N sensors respectively, as needed for proper operation.

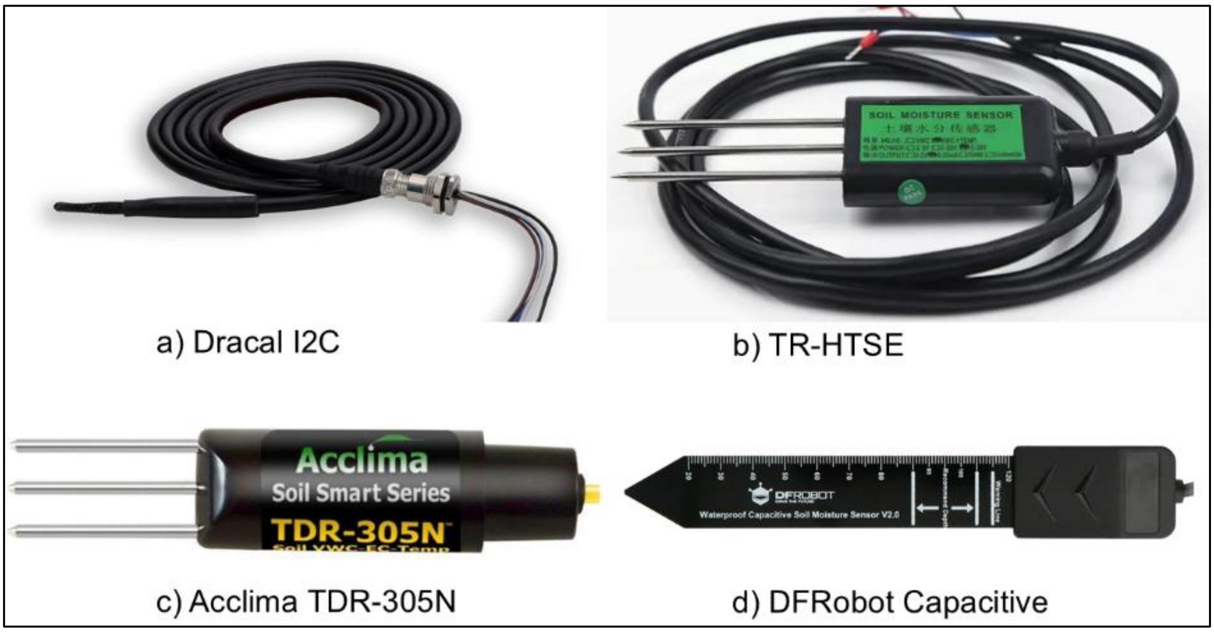

Figure 2: Sensors used: a) Dracal I2C-M8-TRH320 (Dracal Technologies), b) TR-HTSE (Sichuan Weinasa Technology CO., LTD, Veinasa, China), c) Acclima TDR-305N (Acclima, Inc., Meridian, ID, USA), and d) DFRobot Capacitive sensor (DFRobot Shanghai, China)

The Dracal I2C-M8-TRH320 uses a set of high-precision air temperature and relative humidity probes based on the Sensirion SHT31 and SHT35 chips. It uses the I^2C communication protocol to transmit measurements. Additionally, the TR-HTSE Soil VWC is a low-cost sensor that simultaneously measures soil moisture, conductivity and soil temperature using the frequency domain reflectometry (FDR) for moisture and an alternating current bridge method for soil conductivity (Veinasa, n.d). The sensor has three stainless steel needle probes, each 70mm in length, made of high-quality materials that can withstand long-term electrolysis and corrosion from soil acids and alkalis. The sensor operates across a wide supply voltage range of 3.6 to 30 V DC, making it suitable for various field conditions and power sources.

The TDR-305N is a waveform-digitizing integrated time domain reflectometer (TDR) device (Acclima, 2021; Sheng et al., 2024). TDR devices measure the dielectric permittivity of soil water by calculating the time it takes for an electromagnetic wave to travel through the soil (Wilson et al., 2020).This measurement is then used to estimate the water content of the soil. The sensor consists of three stainless-steel rods, each of length 5 cm as indicated by its model name (Acclima, 2021). The device's electronics are embedded in a miniaturized circuit board within the probe head, and it uses the SDI-12 communication protocol via a waterproof cable for data transmission (Sheng et al., 2024).

The DF Robot is a capacitive soil moisture sensor. Its corrosion-resistant coating allows for long-term soil insertion without degradation. The sensor has an onboard voltage regulator, which enables it to operate within range of 3.3 to 5.5 V, thus making it suitable for use with low-voltage microcontrollers. It has three pins: two for power (5 V and Ground) and one analog output pin. The sensor outputs a frequency signal ranging from 260 Hz at high moisture levels to 680 Hz at low moisture levels, with higher frequencies corresponding to lower moisture content (Abdelmoneim et al., 2025).

Table 1: Soil moisture sensing system component specifications and costs

Component	Dimensions (mm)	Mass (g)	Protocol	Maximum sampling rate	Cost (USD)
Feather M0	51 x 23 x 8	5.3	Serial, I2C, SPI	48 MHz	19.95
FeatherWing	50.8 x 22.9 x 1.6	5.1	I2C, SPI	32 KHz	8.95
TDR-305N	150 x 33	121	SDI-12	1 Hz	322.00
TR-HTSE	145 x 45 x 15	1800	FDR	-	70.60
Dracal I^2C	1800	80	I2C	1 MHz	71.99
DF Robot (2)	175 x 30	15	Capacitive	-	37.8
TPS61023	17.8 x 11.3 x 5.6	1.0	-	1 MHz	3.95
TPS61040	15.2 x 10.0 x 2.9	0.1	-	1 MHz	2.95
Solar Panel	110 x 140	90	-	-	34
LiPo Charger	-	-	-	-	14.95
LiPo battery	69 x 54 x 18	155	-	-	24.50
Grand Total					**611.64**

The system was assembled in a structured manner, with each sensor individually connected to the microcontroller and tested separately following the manufacturer's manual (see Table *1* for links) and custom open-source software. Step-by-step assembly instructions to replicate the system are available at https://github.com/OnanAgaba/low-cost-soil-moisture-datalogger.

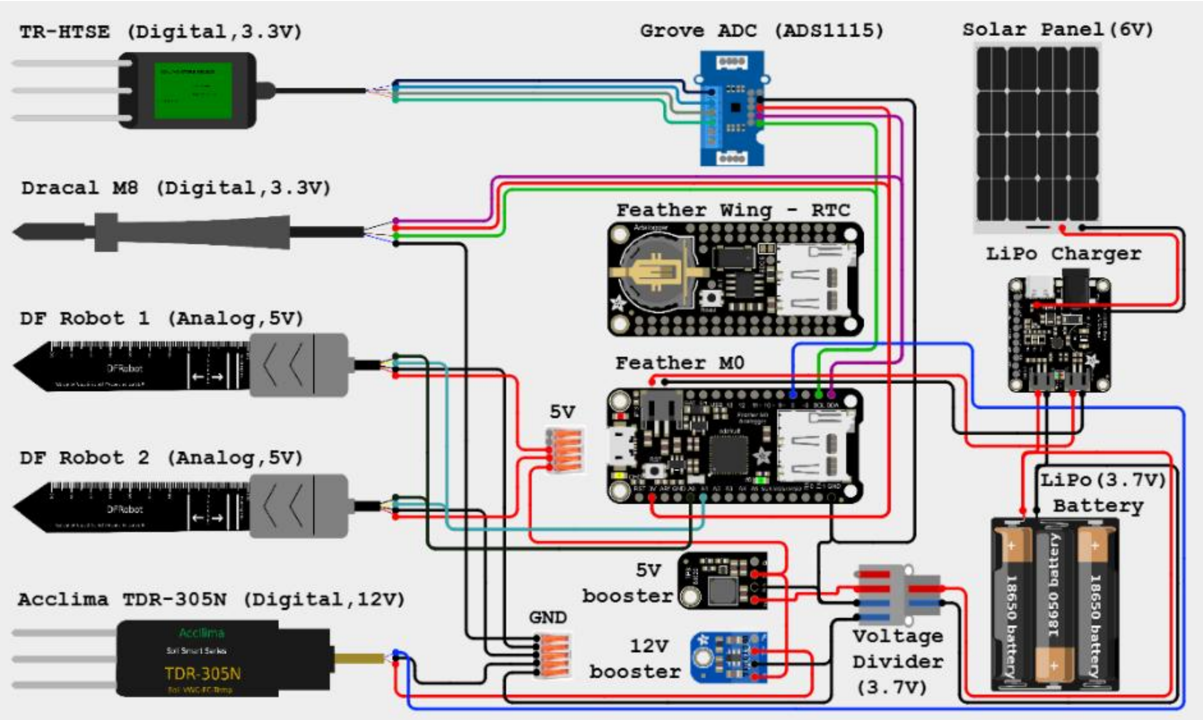

Figure 3: The connection diagram of all components in the soil moisture datalogger

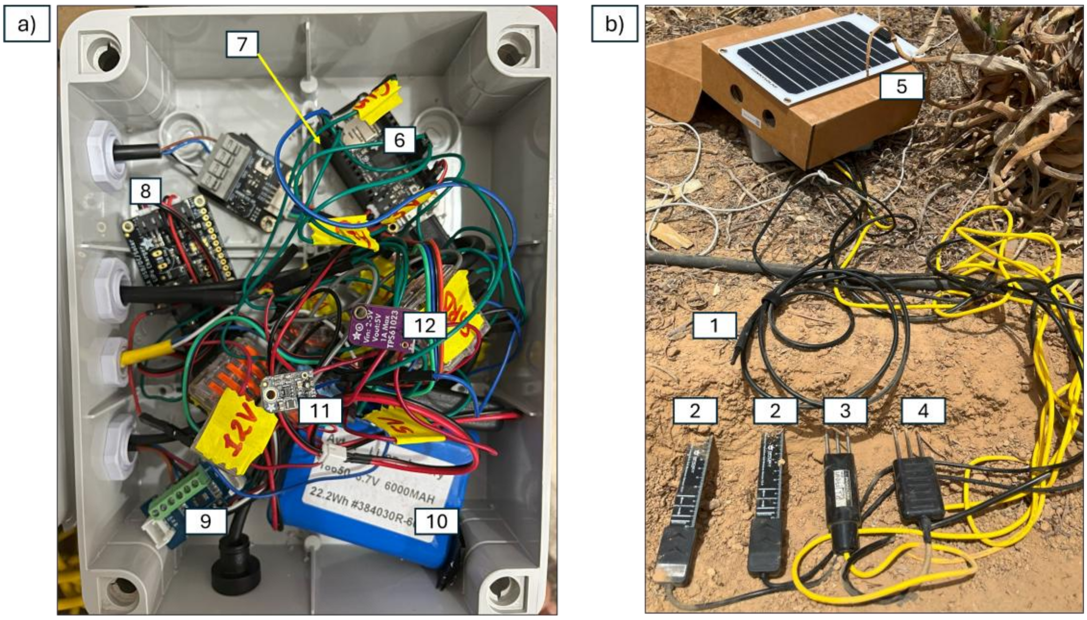

Figure 4: The soil moisture logger set-up: a) components installed in the field: 1) Dracal M8, 2) DFRobot sensors, 3) TDR-305N, 4) TR-HTSE, 5) Solar Panel and 6) Feather M0; b) internal system components housed within a protective enclosure: 7) RTC on FeatherWing, 8) LiPo Charger, 9) ADC, 10) LiPo battery, 11) TPS61023 5V booster, and 12) TPS61040 12V booster.

2.2 Software

The soil moisture logging software was developed using the Arduino Integrated Development Environment (IDE), which is compatible with Windows, Linux, and macOS. Arduino is well-documented, provides easy-to-understand microelectronic resources, and is supported by a large online community (www.arduino.cc) (Fahlbusch & Harrington, 2019). The software was written in C++ using existing Arduino libraries and combined to configure and program the overall system set-up. It runs in a continuous loop (see Figure 5), reading sensor values and saving data every 15 minutes until the logger is turned off or the battery is depleted. During each cycle, sensor values are saved to a CSV file on a micro-SD card. The complete codes, open source licences, logged parameters, connection diagrams, and used libraries can be accessed on GitHub at https://github.com/OnanAgaba/low-cost-soil-moisture-datalogger.

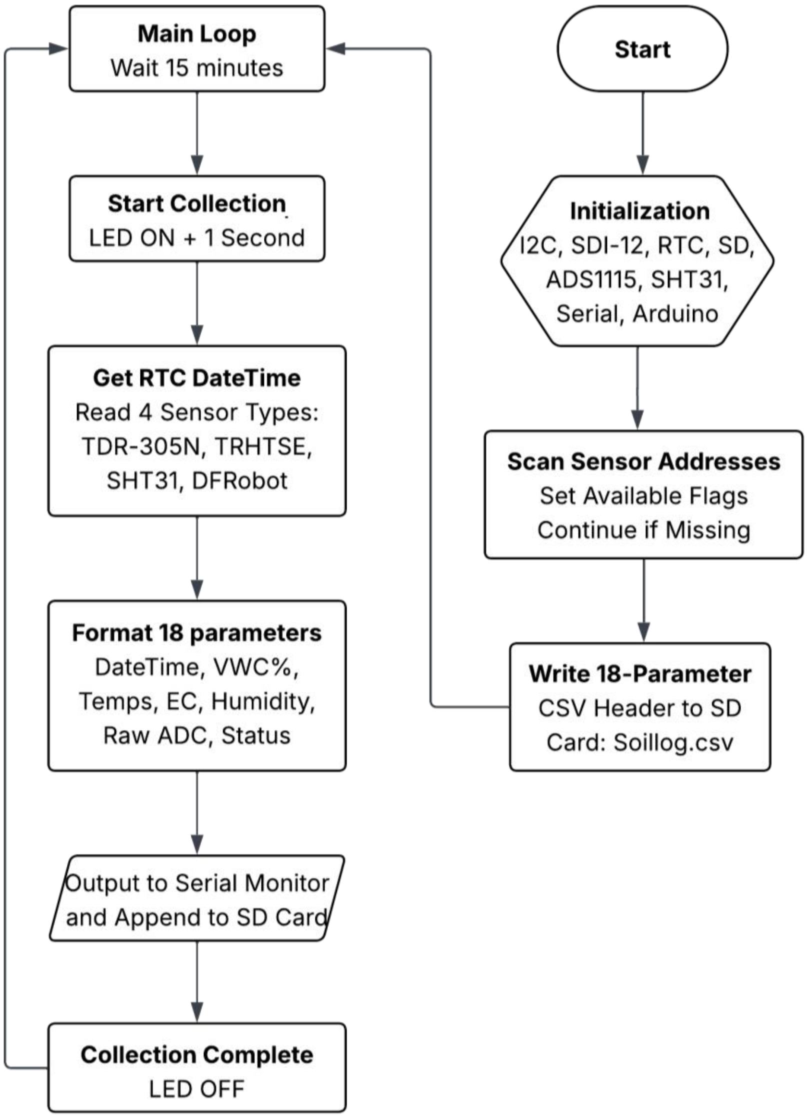

Figure 5: Soil moisture logging flow chart

2.3 Field Deployment

A field experiment was carried out to validate the assembled soil moisture logger (Figure 4) for monitoring soil moisture and other field parameters under arid conditions. The system was installed in the botanical gardens near the water building at Ben-Gurion University of the Negev, Sde Boqer Campus in Midreshet Ben-Gurion. The soil at the installation site is composed of thick loess layers, and the climate is arid, with total annual precipitation of about 90 mm, relative humidity around 20-30%, and a mean annual temperature of 18.9 ∘C (Sede-Boqer, 2025).

To install the sensors, a rectangular pit approximately 15 cm deep was dug to expose the soil profile. Four soil moisture sensors spaced 5 cm apart, were inserted into the soil profile at a depth of 7 cm to ensure complete contact with the surrounding soil. The pit was then back filled after installation to completely cover and secure the sensors. The Dracal sensor was positioned above ground to measure air temperature and relative humidity. The full system was installed and left to log data for three days from July 1 to July 4, 2025. During this time, controlled watering events were applied to increase soil moisture levels to observe sensor responses.

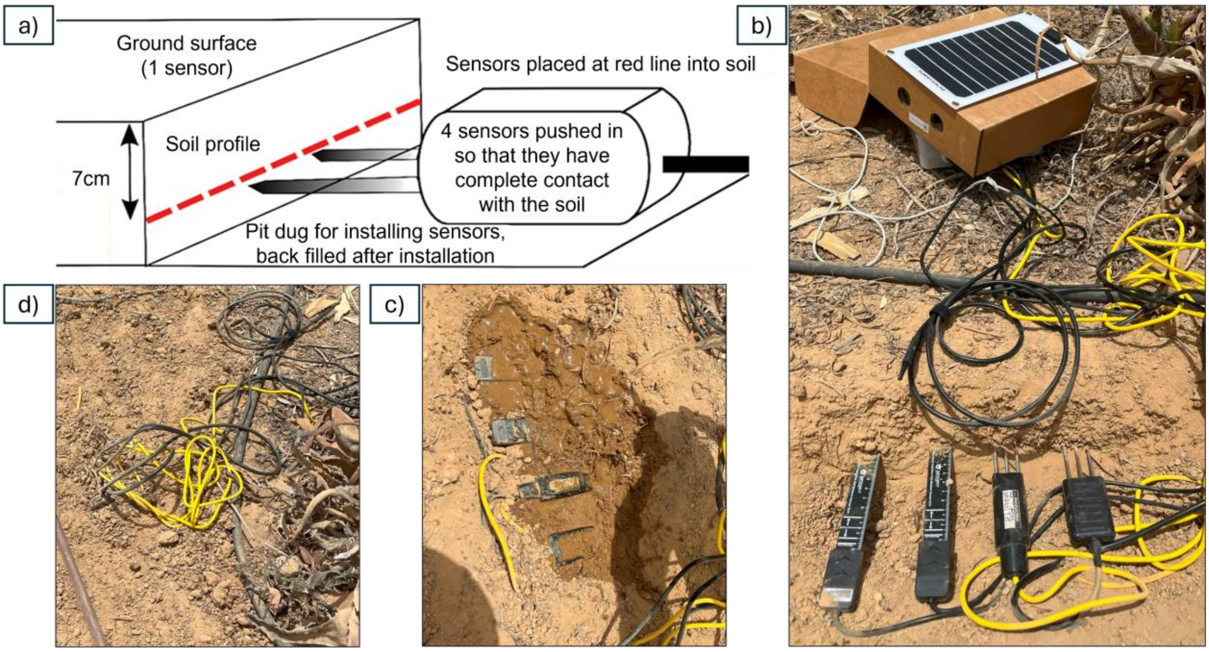

Figure 6: Sequential steps in the field deployment of the soil moisture logger: a) overview of sensor placement, b) sensors installed at 5 cm intervals starting 7 cm below the surface, with the dracal M8 placed on the ground and the enclosure housing the microcontroller and other delicate components covered with a card board to prevent overheating, c) an initial watering event conducted before backfilling to confirm proper data logging, and d) final field site after backfilling, with the system ready for three days of continuous monitoring.

2.4 Sensor Calibration and Performance Evaluation

Due to the indirect measurement nature of low-cost sensors, calibration before field installation is required (Adla et al., 2020). Following established literature methods (Adla et al., 2020; Kushwaha et al., 2024), the capacitive sensors were calibrated to convert raw readings into volumetric water content using linear correlation with a reference TDR sensor. Additionally, the TR-HTSE sensor was calibrated using the manufacturer's equation:

$$y = 52.1x - 25.4$$

where y is the volumetric water content and x is the measured sensor voltage

Sensor performance was evaluated by comparing measurements from each low-cost sensor with TDR values using statistical parameters. The Mean Difference (MD) was calculated to quantify the average difference between the sensor readings and the reference, as follows:

$$MD = \frac{1}{n}\sum_{i=1}^{n}(S_i - R_i)$$

where S_i is the i^{th} reading from the low-cost sensor, R_i is the i^{th} reading from the TDR, and n is the total number of samples.

3. Results and Discussions

3.1 Calibration of Low-Cost Sensors

Raw readings from the DFRobot sensors were calibrated against TDR-measured reference VWC, showing linear correlations with coefficients of determination (R^2) of 0.21 and 0.40 for the DFRobot 1 and 2, respectively. The resulting equations were then used to convert raw sensors readings into soil moisture values, as shown in Figure 7.

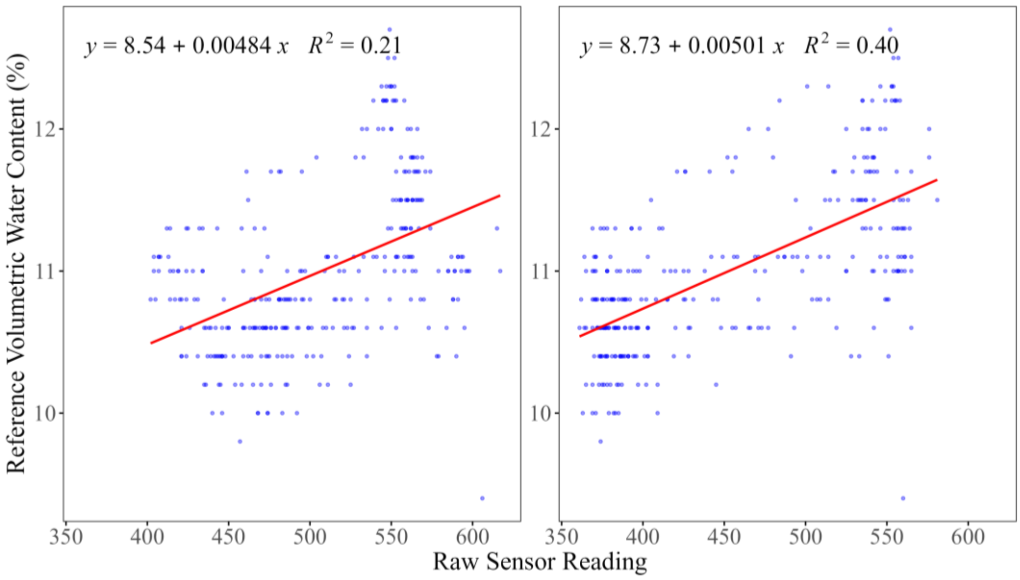

Figure 7: Calibration equations for a) DFRobot 1 and b) DFRobot 2 sensors.

3.2 Soil Moisture

Figure 8 shows the volumetric water content (θ_v) in soil over three days, measured with four sensors. The TR-HTSE sensor consistently recorded the highest θ_v values ranging from 11.55% and 15.22% and displayed clear daily watering cycles. DFRobot 1 and DFRobot 2 showed lower and closely aligned values, ranging from 10.54% to 11.64% and 10.49% to 11.53%, respectively. The TDR305 sensor recorded the lowest and most variable readings (9.4%-12.70%), with increased noise likely due to the high site salinity (2289-5630 µS/cm), a behaviour also observed by Datta et al. (2018) using TDR315. Despite these differences, all sensors captured similar daily fluctuations in θ_v linked to watering events.

Our study findings align with previous sensor comparison studies. For example, Todd et al. (2025) evaluated low-cost sensors ("Cheapies," VH400) against a commercial TDR-310H and additional devices, focusing on both inter- and intra-sensor variability. They found individual variability among low-cost sensors, while commercial sensors delivered more consistent measurements. Similarly, Datta et al. (2018) tested five sensors (TDR, CS655, GS1, SM100, CropX) under controlled and field conditions. TDR sensors provided the best accuracy in both irrigated systems and across soil types, though all sensors were sensitive to salinity and clay content and some exhibited systematic biases.

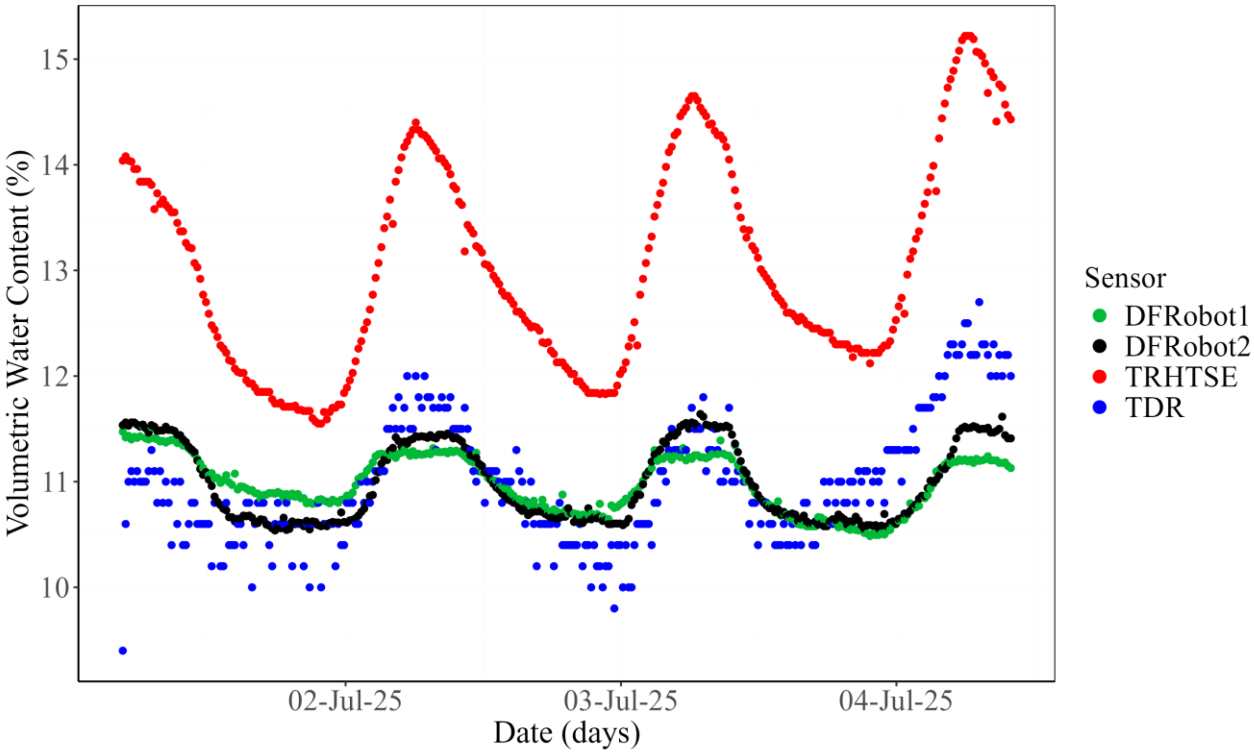

Figure 8: Volumetric moisture measurements from all soil moisture sensors

3.3 Performance Analysis

The DFRobot sensors showed very low bias with Mean Difference values close to zero (-0.006 and -0.001), but exhibited poor precision seen from the wide scatter of data points in Figure 9a) and b) and their low R^2 values (0.21 and 0.40). In contrast, the TR-HTSE sensor in Figure 9c) showed higher precision with data points clustering tightly around the trendline and a higher R^2 (0.639). However, it consistently overestimated values with a large Mean Difference of 2.046. In summary, the DFRobot sensors are unbiased on average but imprecise, while the TRHTSE sensor is more precise but consistently inaccurate.

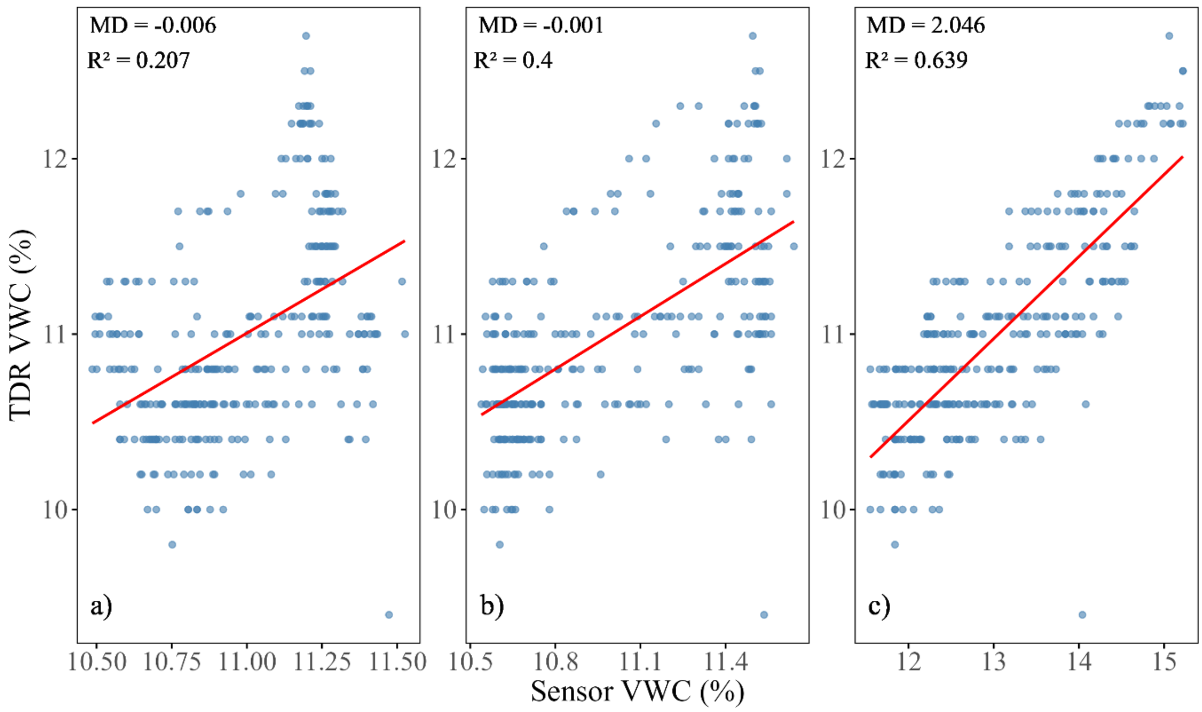

Figure 9: a) TDR against DFRobot1, b)TDR against DFRobot2, c) TDR against TR-HTSE

3.4 Other Measured Parameters

3.4.1 Soil Temperature

Both the TR-HTSE and TDR sensors showed similar daily soil temperature (T_s) patterns with their measurements peaking and dipping in sync (Figure 10). The TDR consistently recorded higher T_s values, ranging from 21.5ºC to 45.8ºC and displayed a smoother, more defined trend compared to the scattered readings of the low-cost TRHTSE sensor, which ranged from 17.23ºC to 34.86ºC. The low-cost sensor showed occasional deviations in measurements likely due to sensor sensitivity and calibration issues. Overall, the temporal alignment of measurements from both sensors suggests that the TRHTSE can reliably reflect soil temperature dynamics under harsh conditions.

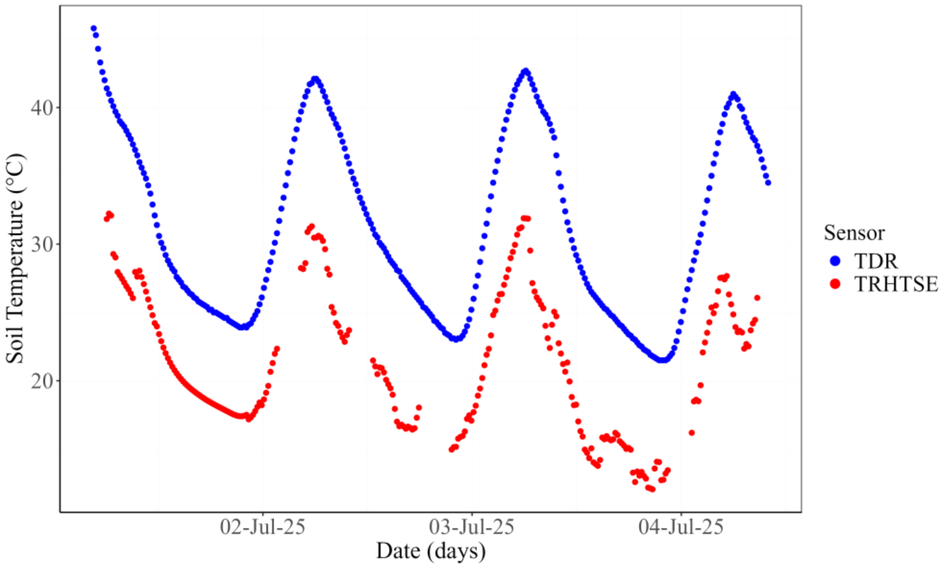

Figure 10: Soil temperature patterns for the TRHTSE and TDR

3.4.2 Air Temperature and Relative Humidity

Figure 11 shows the diurnal fluctuations of air temperature (T_a) and relative humidity (RH_a) recorded by the Dracal sensor over three days. An inverse relationship between the two parameters was observed, consistent with diurnal patterns in arid climates (Kool et al., 2021). T_a followed a daily cycle rising during day hours and falling at night, ranging from 21.62ºC to 55.41ºC. In contrast, RH_a increased as temperature decreased and dropped when temperature rose, ranging from 23.07 to 99.99%. These findings align with those of Kool et al. (2021), who used a Dracal-I2C-TRH320 sensor positioned 1.5 m above the ground in Namib desert. In their study, T_a ranged from 17ºC to 33ºC, while RH_a varied between 25% and 98%.

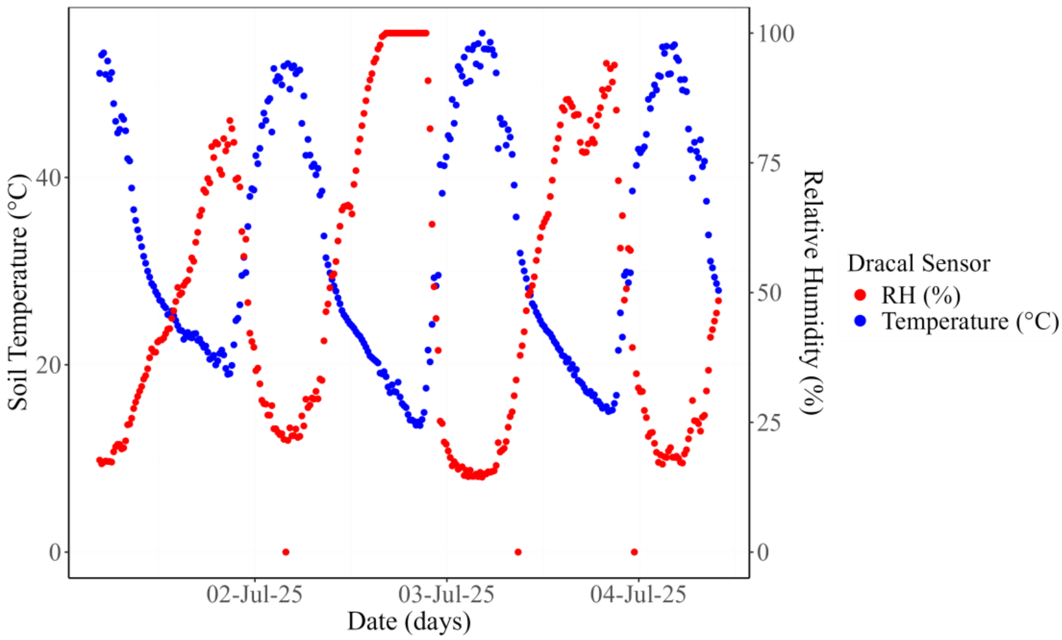

Figure 11: Relative humidity and air temperature fluctuations

4. Challenges and Future Considerations

Several challenges were encountered during the development of this do-it-yourself project. The integration of multiple sensors made prototype assembly complex. This difficulty was due to limited documentation for some low-cost components, which increased the complexity of both software setup and hardware wiring. In addition, this lack of documentation hindered the calibration process. For example, obtaining the calibration equation for the TR-HTSE sensor required contacting the manufacturer to acquire the correct formula. Furthermore, too many connection wires for the different sensors added to system complexity, making the prototype difficult to reproduce without detailed documentation. Another significant limitation was the system's reliance on local data storage via an SD card. This kind of setup required frequent site visits to download data, which is time-consuming and impractical for long-term monitoring.

In the future, conducting site-specific calibration for low-cost sensors will be essential to achieve accurate and reliable measurements. Durability and long-term reliability of the system also require attention because the current setup remains in prototype phase with temporary wiring and exposed electronics. While this made it easier to repair or adjust components during assembly and testing, a more robust design is required for long-term field deployment. This could involve use of weatherproof enclosures and sealed connectors to protect the system under harsh environmental conditions. Furthermore, integrating cloud-based platforms, such as blues.io hub, with modem-enabled data transmission would allow real-time monitoring, improve data accessibility, and reduce field visits. Addressing these challenges by implementing these suggestions will make the system scalable, reliable, more robust, and suitable for long-term monitoring in arid regions.

5. Conclusion

Four soil moisture sensors, i.e., three low-cost types (DFRobot 1, 2, Dracal M-8 I2C, and TR-HTSE) and one commercial (TDR305N) were tested under arid field conditions using a DIY data logger. The TR-HTSE sensor recorded the highest θ_v (11.55-15.22%), DFRobot sensors showed slightly lower and closely aligned values (10.49-11.64%), and the TDR recorded the lowest and most variable θ_v (9.4-12.70%) due to high site salinity. Performance analysis indicated that DFRobot sensors were unbiased but imprecise (MD: -0.006 to -0.001, R^2: 0.21-0.40), while the TR-HTSE sensor was more precise yet consistently overestimated θ_v (MD: 2.046, R^2: 0.639). Both TR-HTSE and TDR sensors captured daily soil temperature patterns, with TDR showing higher temperature ranges (21.5-45.8°C) than TR-HTSE (17.23-34.86°C). Air temperature and relative humidity showed inverse diurnal patterns ranging from 21.62-

55.41°C and 23.07-99.99%, respectively. These results demonstrate the potentials of low-cost sensors for effective soil and environmental monitoring in arid conditions.

Acknowledgements

Although our prior knowledge of sensor technologies was limited, we successfully designed, deployed, and analyzed a multi-sensor system. We sincerely thank DIY course instructor Dr. Elad Levintal and teaching assistants Elyasaf Frieman, Devi Orozcco, and Thi-Thuc Nguyen for their support. We also appreciate the Fritzing forum community and the wealth of open-source resources available. By reading this paper and using our shared GitHub resources, anyone can easily replicate an affordable system to obtain continuous soil moisture data. Lastly, we thank ourselves for persevering; the journey was worthwhile.

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