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Article

Design and Performance Evaluation of a Low-Cost Humidity Sensor for Automated Home Irrigation Systems

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Abstract: This study presents the design, development, and performance evaluation of a low-cost capacitive moisture sensor integrated with an automated home irrigation system, aimed at improving water-use efficiency in small domestic gardens (2 × 3 m^2). Field experiments were conducted using a three-replicate randomized complete block design (RCBD) to evaluate the effects of three main factors: soil texture (sandy, loamy, clay), soil temperature (15 °C, 25 °C, 35 °C), and installation depth (5 cm, 10 cm, 15 cm) on six key performance parameters of the sensor—accuracy, stability, response time, thermal sensitivity, salinity sensitivity, and energy consumption. The results indicated that soil texture had the most significant influence on accuracy, with loamy soil showing the lowest value (2.1%) compared to sandy (4.8%) and clay (3.5%) soils. Stability followed a similar trend, being highest in loamy soil (0.4% SD) and lowest in sandy soil (0.9% SD). Soil temperature strongly affected thermal sensitivity, which increased from 0.05% at 15 °C to 0.12% at 35 °C, and reduced the response time (T_{90}) from 27 seconds at low temperature to 18 seconds at high temperature. Depth of installation is associated with the sensitivity of salinity measurement, with decreased salinity measurement sensitivity (1.8% per S/m^2) and energy consumption (42 mWh/day) for surface mounted probes (5 cm) versus for deeper probes (0.9% per S/m^2 and 36 mWh/day, respectively). These findings highlight the critical importance of considering environmental and operational factors—such as soil texture compatibility, thermal compensation, and optimal probe depth—when designing and applying low-cost moisture sensors for home irrigation. The developed system provides a scientific foundation for creating affordable, accurate, and energy-efficient smart irrigation solutions tailored to domestic green spaces.

Keywords: Moisture Sensor, Soil Texture, Automated Irrigation, Thermal Sensitivity, Energy Efficiency, Water Management.

Introduction

Monitoring soil moisture is of utmost importance due to the need for the implementation of strategies for the water conservation in irrigation. The World Water Commission indicates that 40% of the global population live in areas with "severe water deprivation" [1]. This indicates a clear need for technologies that improve the efficiency of irrigation in agriculture and in the home, and diminish the water consumption.

In national settings, the irrigation of miniature gardening areas is regarded as one of the top offenders of domestic water consumption. Reports show that as much as 30% of national water consumption is used for the irrigation of gardens, and of this, half is wasted through runoff and evaporation [2]. With this information, the need for developing smarter irrigation systems that can better manage water consumption in miniature gardens, backyards, and other vegetation areas around the houses becomes evident.

In this light, the creation of inexpensive soil moisture sensors coupled with automated irrigation technology has been one of the biggest contributors to water conservation and sustainability [3]. The standard soil moisture sensors, in this case, would be the resistive or frequency domain sensors that estimate volumetric water content, and these sensors are highly dependent on calibration, and are heavily influenced by soil texture, temperature, and salinity [4]. With the development of technology, there have been great improvements in the sensors, but the majority of cheap sensors have not been thoroughly tested in the field in varying environmental situations, particularly in the smaller domestic environments.

The ability for sensor-based irrigation systems to save significant amounts of water has been documented in numerous studies. In the case of [5], it was discovered that when soil sensors are properly calibrated, irrigation water consumption can be diminished by as much as 66%. Furthermore, [6] illustrated that in agricultural field cases, irrigation consumption can be reduced by as much as 90% when using wireless sensor networks. From a theoretical perspective, the use of inexpensive sensors has been shown to generate an RMSE (root mean square error) of 1.9% in the case of 16-bit ADC (analog-to-digital converter) systems, whereas high-end commercial sensors have reported an RMSE of 0.95%. With regard to the sensitivity of soil moisture, the capacitive soil moisture sensor and frequency-domain reflectometry (FDR) sensor have demonstrated the potential to be extremely reliable. In regard to installation depth, soil salinity, and soil texture, the aforementioned variables have considerable impacts on sensor performance [7]. Therefore, it is imperative that the placement and calibration methods be optimized to obtain dependable data.

The goal of this study is to design, create, and assess an automated irrigation system capable of effortlessly incorporating capacitive soil moisture sensors. The primary focus of this study is to include the influences of soil texture, soil temperature, and depth on sensor performance when using small-scale domestic settings.

Objective of the study

The findings are expected to assist in the development of affordable, precise, and energy-efficient irrigation technologies for residential and semi-urban applications.

Materials and Methods

1) Trial site and irrigation equipment

As part of the field experiment, a 2 × 3 m^2 home garden in Mosul City, Iraq (36.34°N, 43.13°E) was used to reflect the typical conditions of urban households for irrigation. The plot was designed with a drip irrigation system made of two parallel lateral lines that were 1.0 m apart. Each line had 3 emitters (at 0.5 m spacing). The system was designed to operate at $< 120 \pm 10$ kPa, and each emitter had a discharge rate of 2 $L \cdot h^{-1}$.

Water to the lines was supplied by a submersible DC water pump (12 V, 1.5 A, 3.5 m head, 10 $L \cdot min^{-1}$ flow rate). Water flow was controlled by Solenoid valves (RainBird SV-12, 12 V DC) that were controlled by the microcontroller, and the pump was turned on and off based on the ambient temperature and relative humidity that were measured at 1.5 m above Ground level using a digital Thermo-hygrometer (±0.5 °C, ±2% RH) and to all of the irrigation system and electrical circuit, a microcontroller (Arduino UNO) was used to create the system. The circuit schematic for the system is shown in Figure 1 (System Circuit Diagram).

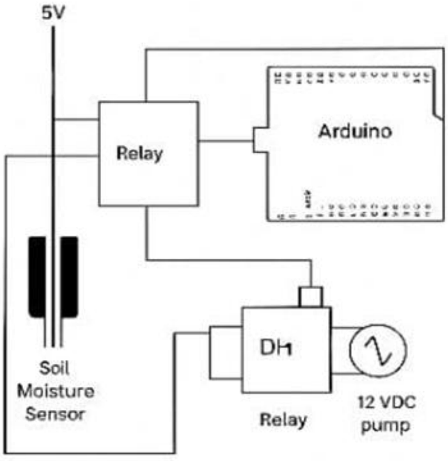

Figure 1. System Circuit Diagram.

2) Design of the Low-Cost Sensor

A capacitive/FDR (frequency-domain reflectometry) type soil moisture sensor was designed and fabricated to detect changes in the soil dielectric constant. The probe consisted of two copper plates (70 ± 10 mm length, 4 ± 1 mm spacing) coated with thin epoxy resin insulation for waterproofing and salt resistance.

An excitation signal of 500 kHz (adjustable within 300–800 kHz) was generated to minimize salinity interference. The analog output was converted to digital form through a 16-bit ADC converter with a 2.048 V reference voltage and a low-noise voltage regulator. Data smoothing was performed using a five-point moving-window digital filter, with readings recorded every 5 minutes.

The connection cable from the probe to the electronic board was 0.5 m shielded wire to reduce parasitic capacitance and electromagnetic interference. The sensor was powered by a 5 V DC supply with a Battery/Line Monitor circuit to record daily power consumption (mWh·day^{-1}).

3) Cultivated material and soil structure

Three representative soil textures—sandy, loamy, and clay—were selected according to the USDA soil classification. Each soil was air-dried, sieved (<5 mm), and homogenized. The physicochemical properties were measured before installation:

Electrical Conductivity (EC): 0.4–0.9 dS·m^{-1}

pH: 6.8–7.5

Bulk density: 1.3–1.6 g·cm^{-3}

The garden plots were planted with short-root grass (Poa pratensis L.) to simulate realistic moisture fluctuation in home irrigation.

4) Experimental Design

A randomized complete block design (RCBD) was applied with three replications (three blocks). Due to limited space, three single-factor experiments were conducted sequentially, keeping other factors constant under reference conditions.

Soil Texture Factor (3 levels): sandy, loamy, and clay; fixed depth = 12 cm; temperature = 25 °C.

Soil Temperature Factor (3 levels): 15 °C, 25 °C, 35 °C, achieved by time-of-day control and partial shading; fixed texture = loamy soil; depth = 12 cm.

Installation Depth Factor (3 levels): 5 cm, 10 cm, and 15 cm; fixed texture = clay soil; fixed temperature = 25 °C; horizontal distance from dripper = 15 ± 1 cm.

Each block contained three treatment units, for a total of 27 experimental units (3 factors × 3 levels × 3 replications).

5) Installation and calibration reference

Each sensor was vertically installed with its longitudinal axis perpendicular to the soil surface. A soft, moist soil layer surrounded the probe to remove air voids. The horizontal distance from the dripper was maintained at 15 ± 1 cm.

For gravimetric calibration, samples were collected under near-dry, medium, and near-saturation conditions. The volumetric water content (θv) was calculated using oven-dry gravimetric measurements at 105 °C until constant weight and converted using bulk density values.

Using polynomial regression of 1st and 2nd degree, equations for R^2 ≥ 0.98 were constructed for the calibration curves for the sensor output and \u03b8\u2096. The reference readings were the result of \u03b8\u2096 laboratory measurements, which are the actual moisture content for accuracy calculations.

A digital thermal probe (±0.5 °C) DS18B20 was used to measure soil temperature, which was then placed adjacent to the sensor head and the salinity was measured (±2%) using a portable EC meter (Hanna HI98331) of which both were compensated in real-time through the controller firmware with coefficient correction equations.

6) Description of the method of machine operation

An automated system was used to continuously measure the soil moisture content. As measurement of moisture content fell below the level set within the system, an Arduino microcontroller activated a relay switch to turn on the water pump [8], .

When moisture content reached the level set within the system, the system then, in an automated fashion, opened the circuit which effectively turned the pump off irrigation . This control system feedback loop was used to keep the soil moisture content at the level required and to control the amount of water used to irrigation the soil. The control system logic and the safety relay are shown in the figure 2 (System Operation Flowchart) [9], [10], [11], [12].

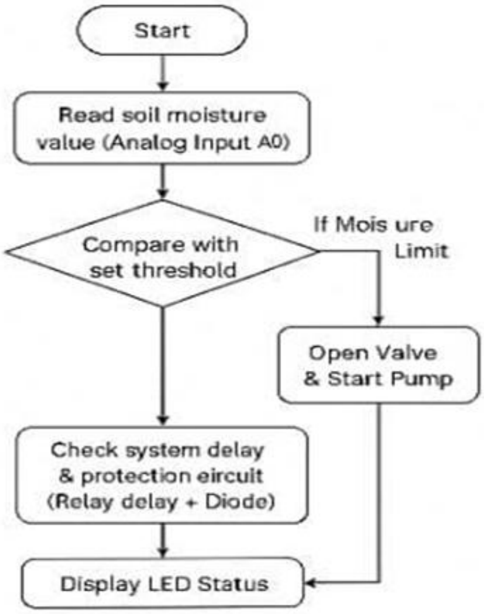

Figure 2. System Operation Flowchart.

7) Methods of calculating studied traits

Sensor performance was evaluated under each treatment based on six main parameters:

accuracy, stability, response time, temperature sensitivity, salinity sensitivity, and energy consumption.

Readings were recorded every 5 minutes, covering multiple wet–dry cycles for each treatment.

1. **Accuracy (%):** The ability of the sensor to give a reading close to the real or reference value of soil moisture.
   Accuracy (%) = Actual Reading – Theoretical Reading / Theoretical Reading – 1
2. **Stability (%SD) :** Calculated as the standard deviation of repeated measurements under constant conditions, expressed as a percentage of the mean.
3. **Response Time (T_{90}) :** The time required for the sensor to reach 90% of the final reading after a sudden change in soil moisture
4. **Temperature Sensitivity (%/°C) :** Represents the relative change in sensor output with changing soil temperature while maintaining constant moisture.
5. **Salinity Sensitivity (% per $S\cdot m^{-1}$)**: The extent to which the reading of the sensor changes as a result of the change in soil salinity when its moisture is constant.
   Sensitivity = Change in Reading / Change in Salinity
6. **Power Consumption (mWh/)**: The amount of energy consumed by the sensor during 24 hours of operation.
7. **Energy Consumed = Voltage * Current * Time**
8. **Statistical Analysis:** Experimental data were analyzed using one-way analysis of variance (ANOVA) to determine the significance of each treatment factor. Mean comparisons were performed using the Least Significant Difference (LSD) test at a significance level of $p \le 0.05$. All analyses were carried out using SPSS v.26 (IBM, USA)

Results and Discussion

Table 1. Effect of soil texture on the studied performance parameters of the moisture sensor.

Power Consumption (mWh/day)	Sensitivity to salinity (%)	Temperature sensitivity (%)	Time Response (Sec)	Stability (%)	Accuracy (%)	Epithets Factors	
40	1.6	0.07	21 seconds	0.9	4.8	**Sandy**	Tissue Soil
38	1.2	0.05	24 seconds	0.4	2.1	loamy	
37	1.0	0.06	28 seconds	0.6	3.5	Clay	

The results in Table 1 indicate that soil texture had a significant effect on all studied parameters.

Sensor accuracy (RMSE %θv) was highest in sandy soil (4.8%) and lowest in loamy soil (2.1%), while clay soil showed an intermediate accuracy of 3.5%. The dielectric response and moisture distribution uniformity and overall improved response and decreased decreased noise interference in loamy soil.

The change in stability (SD %θv) is most noticeable depending on the type of finer the soil texture. Loamy soil showed the most stable soil moisture content (0.4% SD), followed by clay (0.6%), while larger fluctuations (0.9%) were observed in sandy soil because of the larger soil pores and the increased drainage rate.

Response (T_{90}) times were between 21 and 28 seconds. Sandy soil had the fastest response time (21 s) because of the rapid infiltration of the water, and clay soil had the slowest response time (28 s) because it took longer to reach equilibrium due to the capillary redistribution.

The sensitivity to temperature also increased, to 0.07% $\cdot°C^{-1}$ in sandy soil and 0.05%$\cdot°C^{-1}$ in loamy soil. sandy soil has the highest air fraction, which increases the temperature effect on the dielectric constant.

The same pattern is followed by the sensitivity to salinity, with sandy soil (1.6% per $dS\cdot m^{-1}$) having the highest and clay soil (1.0%) having the lowest. the lower response in clay soil indicates a stronger ion-buffering capacity and higher dielectric stability.

Ultimately, power consumption was greater for sandy soil (40 $mWh\cdot day^{-1}$) than for loamy (38) and clay (37), indicating more frequent activation cycles due to faster rate of moisture depletion. This result agrees with Liu *et al.* who found the same texture-dependent behavior for low-cost capacitive sensors.

Table 2. Effect of soil temperature on the studied performance parameters of the moisture sensor.

Power Consumption (mWh/day)	Sensitivity to salinity (%)	Temperature sensitivity (%)	Time Response (Sec)	Stability (%)	Accuracy (%)	Epithets Factors	
36	1.3	0.05	27	0.5	2.9	15	temperature
38	1.4	0.08	22	0.6	3.1	25	
41	1.5	0.12	18	0.8	3.4	35	

References to Table 2 indicate the significance of soil temperature on the majority of the soil measurement sensor parameters.

The accuracy of the measurement sensors decreased as soil temperature increased. For example, sensor accuracy decreased from2.9% at 15 °C to 3.4% at 35 °C. The electronics of the sensors, specifically reference oscillator circuits, experience thermal drift, causing a loss of measurement accuracy.

Sensor measurement stability decreased as soil temperature increased. The standard deviation of the soil measurements increased from 0.5% to 0.8% as soil temperature increased due to increased thermal expansion and the resulting variations of the dielectric soil constants.

The soil measurement sensors also exhibited a significant reduction in water response time as soil temperature increased. The response time, T90, decreased from27 seconds at 15 °C to 18 seconds at 35 °C, because higher temperatures also lead to a lower viscosity of water, resulting in an increased rate of wetting of the sensor probes.

Temperature sensitivity increased from 0.05%$\cdot°C^{-1}$ at 15 °C to 0.12%$\cdot°C^{-1}$ at 35 °C. The results of Schwaback, 2023 are consistent with the results from previous research which states that the dielectric sensors show increased temperature of soil sensor detection due to the drift of capacitance [13].

The sensitivity of sensor measurement to saline soil also increased with increased temperature from 1.3 to 1.5 % per $dS\cdot m^{-1}$ due to the increased ionic mobility.

In the same fashion, increased energy consumption from 36 to 41 $mWh\cdot day^{-1}$ was due to ambient temperature rise increasing both leakage current and system activation frequency. In general, these trends show that the development of temperature compensation models is required when considering the deployment of low-cost capacitive sensors in field scenarios.

Table 3. Effect of probe installation depth on the studied performance parameters of the moisture sensor.

Power Consumption (mWh/day)	Sensitivity to salinity (%)	Temperature sensitivity (%)	Time Response (Sec)	Stability (%)	Accuracy (%)	Epithets Factors	
42	1.8	0.09	19	0.7	3.5	5cm	Depth Installing the probe
38	1.3	0.07	23	0.6	3.0	10cm	
36	0.9	0.06	27	0.5	2.7	15cm	

Table 3 also displays the root mean square error (RMSE) and moisture sensor depth measurements (5 cm to 15 cm), where RMSE improved from 3.5% at 5 cm to 2.7% at 15 cm RMSE for moisture sensors at 15 cm depth has improved sensor accuracy [14]. Greater moisture stability and decreased evaporation at the soil surface resulted in better accuracy at greater depths.

At greater depths, the 0.5% drop in SD indicates greater stability at the lower air-soil interfaces, and thus, soil moisture measurements also have greater stability.

Depth at which soil moisture sensors are installed also affects the time to reach 90% (T90) soil moisture content, where T90 soil moisture content was 19 s at 5 cm and 27 s at 15 cm. This is because deeper soil horizons slow down the movement of water compared to those in shallow soil horizons.

T°C sensitivity also improved with depth installations. 0.09$\%\cdot{}^{\circ}C^{-1}$ zero sensitivity at 5 cm depth improved to 0.06$\%\cdot{}^{\circ}C^{-1}$ zero sensitivity at 15 cm depth. This indicates that soil thermal conditions were more stable at greater depths.

5 cm depth installation showed the high of 1.8% sensitivity to changes in salinity, while installations at 15 cm depth showed the low of 0.9% sensitivity to changes in salinity. This means that surface soil salt has a greater impact on a soil moisture sensor's readings compared to soil moisture sensors that are installed at greater depths which are less sensitive to changes in electrical conductivity (EC) [15].

Lastly, moisture sensors at shallower depths (5 – 15 cm) less power, i.e., less than 42 to 36 mWh$\cdot$day^{-1}, than those at greater depths which means that moisture sensors located at shallower depths are activated less, and thus, less irrigation was done to those soil.

These findings together show that optimizing for accuracy, stability, and energy efficiency, a sensor should be installed at a depth of 10–15 cm. This agrees with previous studies, such as [2], [15].

Conclusion

1. The results of this study show that a number of environmental and installation factors such as soil texture, soil temperature and probe depth have a strong influence on the performance of the low-cost capacitive soil moisture sensor. The results demonstrated how these variables affected the soil moisture sensor's accuracy, stability and response time, which are important for effective irrigation management.
2. The response of the sensor was greatest in sandy soil with high permeability and rapid moisture changes, while in loamy soil the readings were the most stable with the least amount of fluctuations. This suggests that for low-cost capacitive sensors to yield good results, their calibration will have to take into consideration the soil type.
3. Soil temperature also had a clear influence on the sensor, as elevated temperature increased the sensor response time and increased the temperature, which increased the thermal sensitivity and energy consumption. This means that in warm climates, thermal compensation algorithms should be used to improve accuracy.

4. In terms of probe installation depth, shallow placement (5 cm) increased responsiveness but sensitivity to salinity and power consumption, whereas deeper placement (10 to 15 cm) increased stability and energy efficiency. Therefore, a moderate depth provides a balanced operational capability ideal for extended use.
5. In general, the results demonstrate that 25-35 °C (moderately warm temperature) and 10 cm (moderately deep) placements of the sensor, primarily in loamy or sandy soils, provide a reasonable trade-off for precision, stability, and energy efficiency.
6. To summarize, the created low-cost sensor could be easily incorporated into automated and solar-powered smart irrigation systems. However, additional testing for robustness and flexibility in varying climatic conditions and soil salinity is required to support large-scale use in farming practices.

Recommendations

Using the test results and the performance assessment of the created low-cost soil moisture sensor, a number of technical and practical suggestions have been made to improve the soil moisture sensor's precision, dependability, and use in automated irrigation systems.

1. Field Calibration: Prior to installation, each sensor should be calibrated in-situ to account for the local soil's texture, structure, and environmental conditions. Correct field calibration reduces the likelihood of deviation in sensor readings and increases the measurement accuracy, regardless of the soil type.
2. Future designs should consider incorporating mechanisms or algorithms that automatically correct thermal and salinity fluctuations to ensure consistent data records.
3. To accurately reflect the soil moisture that is available to the plant, the moisture probe should be strategically placed within the active root zone, typically 10-15 cm below the surface and 10-20 cm from the drip emitter.
4. The use of components that consume minimal power is especially important for designs that incorporate renewable (solar) energy sources, as providing for the energy needs of the wireless irrigation system contributes to sustainability and reduces operational limitations.
5. To enable data-driven irrigation systems to make decisions and carry out actions in real-time, irrigation controllers should be equipped with sensors that detect conditions and respond in less than 30 seconds.
6. Field tests of insulation materials and data signal stability for long-term (weeks to months) are needed to evaluate the data drift of the systems.
7. IoT Platform Integration: The merging of sensors with Internet of Things (IoT) systems using low-energy communication methods (i.e., LoRaWAN, Zigbee) is suggested for remote monitoring, responsive irrigation planning, and aided decision-making through data analysis.
8. Value Added to Water Demand Management: The use of stable and accurate low-cost sensors is likely to support sustainable water management practices, with a potential reduction of 50–70% water use in small-scale and urban irrigation systems.
9. Anticipated Research: Additional research is required to test the sensor performance in various soil types, salinities, and climates. Additionally, upcoming research can focus on developing machine learning-based calibration methods and IoT-cloud architecture for intelligent irrigation management.

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