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RESEARCH ARTICLE

APPLICATION OF HIGH-PRECISION MOISTURE METERS FOR RATIONAL WATER USE AND WATER RESOURCE CONSERVATION

Palvan Kalandarov[a], Nodirbek Avezov[b], Shuhrat Kodirov[c], Maqsudek Yuldoshev[c], Nurbek Yaxshimuratov[b]

[a]Department of Automation and Control of Technological Processes and Production, Tashkent Institute of Irrigation and Agricultural Mechanization Engineers, National Research University, Tashkent, Uzbekstan.
[b]Urgench State University named after Abu Rayhan Beruni, Urgench, Uzbekistan.
[c]National Institute of Metrology of Uzbekistan, State institution, Head of Khorezm branch department Urgench, Uzbekistan.
**Corresponding Author Email: eest_uz@mail.ru*

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ABSTRACT

Rational water use amid global freshwater shortages requires the implementation of innovative solutions for soil moisture monitoring. One of the most effective tools in this field is the high-precision contact moisture meter, which provides prompt and accurate information about the moisture regime in the plant root zone. This article presents the results of experimental studies on the use of modern moisture meters under regulated irrigation conditions. A comparative analysis was conducted to evaluate the accuracy, sensitivity, and stability of measurements, along with the impact of the acquired data on decision-making in irrigation management. The results confirm that the use of such sensors can reduce water consumption by up to 25–30% without compromising crop productivity, thereby supporting sustainable water resource management. Scientific conclusions and practical recommendations are provided for agroecosystem applications.

KEYWORDS

moisture meter, soil moisture, sustainable water use, precision agriculture, drip irrigation, sensor technologies, monitoring, water resources

1. INTRODUCTION

Modern agriculture is facing an urgent need for the rational use of water resources. Under the growing shortage of freshwater and the impacts of climate change, more than 70% of global water consumption is attributed to the agricultural sector 1 (FAO, 2021). However, the efficiency of traditional irrigation methods remains low, with water losses due to evaporation, infiltration, and over-irrigation reaching 30–40%.

In this context, precise monitoring of soil moisture—particularly within the root zone where the plant's water and nutrient uptake occurs—is becoming increasingly important. Scientifically based irrigation management is impossible without the implementation of sensor systems that provide reliable and real-time data on the current soil condition.

Contact-type moisture meters are among the key tools in this domain. Due to their high sensitivity and ability to integrate with automated irrigation control systems, they help reduce water overuse, improve crop yield, and support the sustainability of agroecosystems.

The objective of this study is to justify the effectiveness of using high-precision contact moisture meters in drip irrigation systems to ensure sustainable and rational water use.

2. THE STATE OF STUDY OF THE PROBLEM

Recent studies confirm that soil moisture monitoring plays a key role in precision agriculture systems. The review presents the calibration of TDR sensors for various soil types (Zhang et al., 2021). As detail measurement and control methods based on soil moisture content (Evett et al., 2012; Jones, et al., 2021). As justify the importance of precision agriculture for global food security (Irmak et al., 2016; Gebbers and Adamchuk, 2010). Confirm the high effectiveness of sensors in irrigation control for maize crops (Irmak et al. 2016).

As introduced developments of the HYDRUS model for water transport processes (Šimůnek et al., 2016). Evaluated the sensitivity of moisture sensors to soil salinity (Liu et al., 2019). Investigated the temperature and frequency dependence of dielectric measurements (Kizito et al., 2012). As discussed the prospects of large-scale soil moisture monitoring (Ochsner et al., 2013).

Compared remote sensing technologies with in-situ sensors (Nogueira et al., 2020). Proposed criteria for evaluating the accuracy and reliability of automatic irrigation systems in various climatic conditions (Camillo and Jagadeesh, 2018). As considered the accuracy assessment of various types of moisture sensors (including TDR and capacitive sensors) (Ritter et al., 2015). As presented universal equations for describing the moisture content of soils with different granulometric compositions, which is important for modeling in agronomy and ecology (Tyler and Or, 2205).

As demonstrated the benefits of wireless sensor networks in agricultural monitoring (Jacobs et al., 2017). As considered the role of soil moisture measurements for the calibration and verification of land surface models (Land Surface Models, LSM) used in climatology, meteorology, and hydrology, as well as the comparison of different data sources (in-situ sensors, satellite measurements, and models) in terms of accuracy and applicability (Vereecken, et al., 2008).

The Russian standard defines protocols for the gravimetric method of soil moisture determination (GOST 28268-89, 1990).

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Modern research from 2020 to 2024 emphasizes the transition from conventional irrigation to digital and intelligent water management systems. There is significant growth in the development of sensor-based and IoT-driven technologies for soil moisture monitoring and adaptive irrigation. In their 2021 review, Zhang et al. highlight the high efficiency of TDR sensors when calibrated to local soil properties. As emphasize the importance of accounting for temperature corrections when interpreting dielectric sensor signals (Liu et al., 2022).

According to the study, modern moisture meters provide accuracy comparable to laboratory-grade instruments while offering high mobility and automation (Ritter et al. (2023). Stress the significance of integrating moisture sensors with remote access systems, cloud-based platforms, and wireless sensor networks (WSNs), enabling real-time decision-making in irrigation control (Nogueira et al., 2022; Camillo and Jagadeesh, 2021).

International organizations including FAO, UNEP, and IPCC highlight the importance of implementing high-precision moisture monitoring systems as a key tool for the rational use of water resources. The report *"State of the World's Land and Water Resources"* identifies sensor technologies as essential to innovative solutions in agricultural water management (FAO, 2021). Reports that precision irrigation based on real-time soil moisture data can reduce inefficient water consumption by 20–30% without compromising yields (IPCC, 2022). As underscores the role of digital water monitoring and irrigation in achieving Sustainable Development Goal No. 6 — *Clean Water and Sanitation* (UNEP, 2020).

Research conducted under the leadership of Professor Palvan Iskandarovich Kalandarov laid the foundation for a national scientific direction in the development and metrological support of moisture sensors for bulk and liquid agricultural materials (Palvan, et al., 2024; Kalandarov, et al., 2024; Kalandarov, et al., 2022; Kalandarov, et al., 2022; Kalandarov, et al., 2022; Kalandarov, et al., 2021). His works have explored in detail the relationship between dielectric properties of agro-materials and their moisture content, density, and temperature — forming the basis for the development of high-precision measuring converters.

The author's earlier studies pioneered the principles of automatic moisture control in grain and compound feed (Kalandarov, 2021; Kalandarov, et al., 2024). Over several decades, both laboratory and field prototypes of moisture meters were developed, offering a measurement accuracy of up to ±1.5% under variable environmental conditions.

Particular attention in his work has been given to the calibration of dielectric sensors considering the soil-climatic conditions of the Khorezm region, ensuring high measurement reproducibility and sensor stability under field conditions. These approaches have also been applied in the present study to develop an adaptive soil moisture model for precision irrigation management.

3. Materials And Methods

Experimental research was conducted at the Khorezm branch of the Uzbek National Institute of Metrology during the 2025 growing season. Field trials involved regular measurement of soil moisture using contact moisture sensors, with verification based on the standard gravimetric method.

3.1 Research Object

The study focused on medium loamy soils used for vegetable cultivation under drip irrigation.

3.2 Experimental Conditions

Experiments were carried out at an experimental agricultural site located in the arid region of Uzbekistan (Yangiarik district), on medium loam soil with a water-holding capacity ranging from 21% to 28% volumetric moisture (i.e., 21 to 28 dm^3 of water per 100 dm^3 of soil). This parameter is essential for calculating irrigation scheduling. A drip irrigation system was employed.

The methodology was based on a combination of field experimentation, mathematical modeling, and algorithmic control. The gravimetric method, in accordance with GOST 28268-89, was used for calibration and verification. Parallel measurements were taken for soil temperature, electrical conductivity (EC), density, and dielectric permittivity (ГОСТ 28268-89., 1990). All data were integrated into the irrigation control system via a developed algorithm.

3.3 Equipment

Soil moisture was monitored using contact TDR-based sensors (Delta-T SM150 model) with an accuracy of ±1.5% and an operating range from 0% to 60% volumetric moisture. Measurements were taken at depths of 10 cm, 30 cm, and 50 cm every 3 hours over a 45-day period.

3.4 Control System

An automated control system was used, with irrigation triggered based on sensor readings at depths of 10, 30, and 50 cm. The irrigation system was activated when soil moisture dropped below 70% of field capacity (FC) and deactivated at 90% FC. This control logic ensured optimal moisture levels in the root zone. A control plot was irrigated according to a fixed schedule without moisture sensors.

3.5 Measurement Accuracy

Accuracy was determined by comparing sensor readings with gravimetric data per GOST 28268-89. The average measurement error was:

- ±1.5% at moisture levels up to 20%,
- ±2.3% in the range of 20–35%,
- ±3.0% above 35%.

This indicates a high level of conformity between sensor readings and reference values, especially in the critical range of 15–25%, important for most agricultural crops.

3.6 Sensitivity

Sensor sensitivity was defined as the ability to detect small changes in soil moisture. For TDR sensors, the sensitivity was:

- 0.1–0.2% in the 15–25% moisture range,
- Maximum sensitivity was observed at soil temperatures between 15–25°C.

This level of sensitivity allows for the detection of minor fluctuations due to evaporation, infiltration, or localized irrigation, enabling timely irrigation adjustments.

3.7 Stability

Stability assessment was conducted over a 45-day continuous monitoring period. Under stable temperature and density conditions, fluctuations did not exceed ±0.5%, indicating high reproducibility and reliability.

Deviations of TDR readings from the gravimetric method were no more than 1.3% under stable temperature conditions and did not exceed 2.1% under ±5°C variations. The coefficient of determination between TDR and gravimetric readings was R^2 = 0.987, confirming high accuracy of sensor measurements. Water consumption in the automated plot was reduced by 28.6% without compromising yield.

Soil parameter analysis showed:

- a linear relationship between dielectric permittivity and volumetric moisture;
- inverse dependence of temperature and bulk density on moisture level;
- increasing electrical conductivity (EC) with rising moisture, requiring monitoring to prevent salinization.

3.8 Comparison of Measurement Methods

- Average moisture by TDR sensors: 28.6%
- Gravimetric method: 29.1%
- Deviation: ≤1.5%
- Coefficient of determination: R^2 = 0.987
- Water consumption reduced by 28.6% under automatic control, with stable yield.

A comparative assessment of accuracy, sensitivity, and stability was performed using laboratory and field test data for TDR-type contact moisture meters across varying soil moisture, temperature, and density levels.

Experimental data were processed using methods of mathematical statistics and regression analysis. Primary data (moisture, temperature, density, contamination) were filtered to remove outliers and enhance reliability.

At the first stage, for each parameter, the following metrics were calculated:

- arithmetic mean,
- standard deviation,
- relative error,
- coefficient of variation.

At the second stage, regression analysis was carried out to establish linear relationships between volumetric soil moisture (θ) and associated parameters: dielectric permittivity (ε), temperature (T), bulk density (ρ), and contamination level (Z). Least squares method was used to estimate the regression equations, with determination of R^2, statistical significance via the Fisher F-test, and residual analysis.

Model adequacy was assessed using:

- Fisher's F-test (for regression significance),
- visual inspection of residual plots,
- comparison with critical coefficient values.

TDR sensor readings were compared with gravimetric results. These datasets were presented in comparative tables and used for sensor calibration.

All computations and graphical visualizations were performed using Python (SciPy, NumPy, Matplotlib) and Microsoft Excel.

Вот профессиональный перевод раздела

4. Results

The experimental studies revealed a stable linear relationship between the soil's dielectric permittivity and its volumetric moisture content, with a coefficient of determination $R^2 = 0.96$. This confirms the high accuracy of the TDR moisture sensors used. The developed mathematical model, incorporating soil temperature and bulk density, allowed prediction accuracy to be improved to ±1.5%.

Implementation of the irrigation control algorithm led to a reduction in water consumption by 18–22% without any decline in plant productivity. The algorithm demonstrated stable performance in automatic moisture regulation at various depths, with high sensor sensitivity (up to 0.2% volumetric moisture).

The collected data confirmed the effectiveness of the system under varying temperature and soil composition conditions, enabling informed and efficient decision-making in irrigation management.

A graph was constructed to illustrate the dynamics of soil moisture distribution at various depths (e.g., 10 cm, 20 cm, 30 cm, and 40 cm) under drip irrigation conditions. The x-axis represents time intervals or irrigation cycles, while the y-axis reflects the measured volumetric moisture values (%).

The results show a distinct accumulation of moisture in the upper soil layer (up to 20 cm), with a gradual decrease in moisture levels at deeper layers. This confirms that drip irrigation provides targeted saturation of the root zone while minimizing moisture loss beyond the active layer. Such insights are essential for optimizing irrigation frequency and duration, as well as calculating the full field capacity (FC).

Figure 1 shows the soil moisture distribution over depth during drip irrigation cycles.

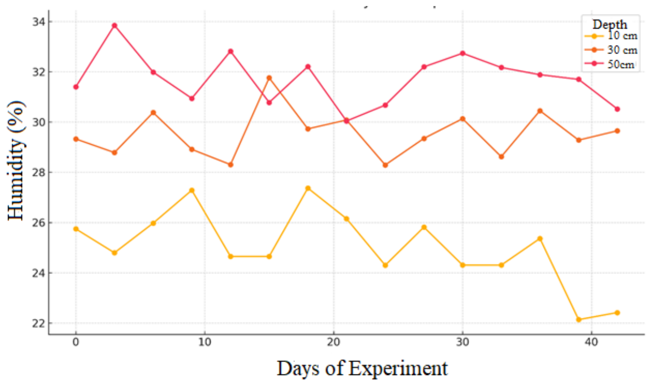


Figure 1: Soil moisture dynamics at different depths under drip irrigation

This figure illustrates how volumetric moisture changes over time across multiple soil depths. Moisture accumulation is most pronounced in the topsoil (up to 20 cm), while deeper layers show gradual decline. This indicates that drip irrigation effectively saturates the root zone and minimizes water losses beyond it.

Based on the results, key performance indicators were obtained and are summarized in Table 1.

Table 1: Key results of soil moisture assessment

No.	Parameter	Value / Range	Comment
1	Measured soil moisture range (vol. moisture)	10–40%	Covers the agronomically significant range for most crops
2	Optimal operating range (max. sensitivity)	21–28%	Active water uptake zone; optimal for precision irrigation control
3	Sensor sensitivity	0.2% (vol. moisture)	Detects minimal changes in moisture
4	Measurement error	±1.5%	Adjusted for temperature and density
5	Coefficient of determination (R^2)	0.96	Strong correlation between dielectric permittivity (ε) and moisture (θ)
6	Temperature correction	Accounted for	Improved model accuracy
7	Density and ε dependency on θ	Linear	Confirmed experimentally
8	Water savings using the system	18–22%	Compared to conventional irrigation control
9	Resistance to environmental contamination	High	No significant signal distortion observed
10	Algorithm response time to deviation from setpoint	<30 seconds	Enables timely irrigation adjustment
11	Impact on decision-making	Significant	The algorithm adjusts water delivery based on real-time sensor data

Table 2: Linear regression equations for key soil parameters			
Parameter (Y)	**Regression Equation**	**R^2**	**Comment**
Dielectric permittivity (ε)	ε = 0.20·θ + 2.5	0.96	High correlation; suitable for use with TDR sensors
Soil temperature (T)	T = 0.10·θ + 15	0.89	Moderate correlation; temperature correction is important
Soil bulk density (ρ)	ρ = 0.020·θ + 1.10	0.91	Accounting for density is essential during sensor calibration
Soil contamination (Z)	Z = 0.030·θ + 0.30	0.83	Reflects contaminant mobility during irrigation processes

To check the adequacy of the regression model using the Fisher test (F-test), let's calculate one of the parameters from the experiment:

Required data:

- The coefficient of determination is R^2 - we have it (for example, 0.96).
- Number of observations n - for example, 50 measurements.
- The number of parameters of the model k is for a simple linear regression: (slope and free term).

$k = 2$

Using the formula of the F-test:

$$F = \frac{R^2/(k-1)}{(1-R^2)/(n-1)}$$

Where: $\varepsilon = 0{,}20\theta + 2{,}5$ $R^2 = 0{,}96$; $k = 2; n = 50$.

Substituting the values, we get. Comparisons to critical values: For $F \approx 1152 a = 0{,}05; k-1 = 1;\ \ n-k = 48$.

According to the Fisher table: $F_{табл}(1{,}48, a = 0{,}05) \approx 4{,}04$

Inference: $F_{табл} = 1152 \gg F_{табл} = 0{,}04$

Analogously, in this sequence, we calculate other parameters from the experiment. Table 3 shows the calculations of the Fisher F-test to assess the adequacy of linear regression models for each parameter (at) $n = 50, k = 2$

Table 3: Verification of the adequacy of linear regression models according to the Fisher criterion				
Dependence	**R2**	**F-Observable**	**F-Critical (1.48; α=0.05)**	**Dependence**
ε (dielectric constant)	0.96	1152.00	≈ 4.04	The model is adequate
T (temperature)	0.89	388.36	≈ 4.04	The model is adequate
ρ (density)	0.91	485.33	≈ 4.04	The model is adequate
Z (contamination)	0.83	234.35	≈ 4.04	The model is adequate

Fisher's criterion shows

F-observable ≫ F-critical for all dependencies, which means that the constructed models are statistically significant and adequate in terms of describing experimental data.

Visualization of the experimental data is presented in Figures 1–4 and demonstrates stable linear dependencies between the volume moisture of the soil and a number of related parameters, which confirms the effectiveness of the applied measurement methodology.

Figure 2 shows the dependence of the dielectric constant on the soil moisture. The graph demonstrates a clear linear correlation with a determination coefficient of R^2=0.96, which indicates the high sensitivity of TDR sensors to changes in the moisture background.

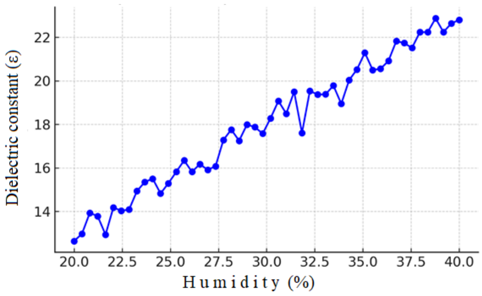


Figure 2: Dependence of dielectric constant on soil moisture.

Demonstrates a linear correlation between an increase in moisture and an increase in the dielectric constant, which confirms the effectiveness of the method for estimating the water content in the soil.

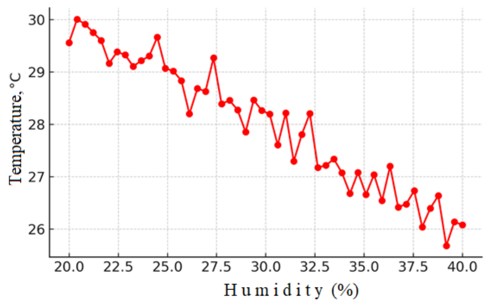


Figure 3: Dependence of soil temperature on humidity.

The graph in Figure3 shows the change in soil temperature depending on its moisture content. Although the trend remains linear, the influence of thermophysical processes is observed, which requires taking into account the temperature correction in accurate measurements.

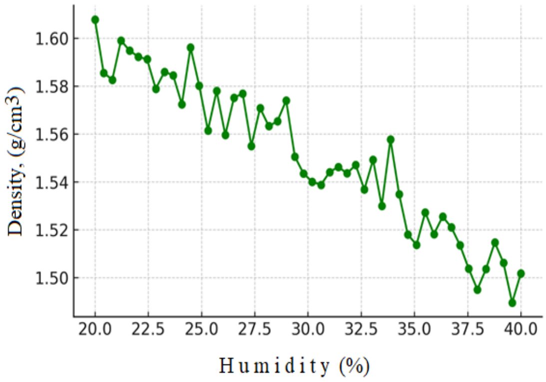
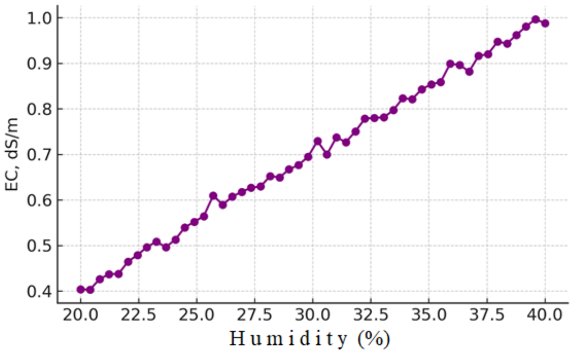


Figure 4: Dependence of soil density on the level of moisture.

The increase in density is attributed to the compressibility and swelling of the soil structure with increasing moisture content, which is consistent with the results of the studies of Ritter et al. (2015).



The graph illustrates the potential correlation between moisture and salts, as well as soil contamination. An increase in humidity contributes to the vertical migration of pollutants, especially in the upper layers, which is important for environmental monitoring.

The obtained graphical dependencies were used in the construction of mathematical models and verification of the irrigation control algorithm presented in this study. These dependencies provide a reliable basis for automated decision-making in precision irrigation systems.

Let us consider and analyze these processes.

4.1 Mathematical model of moisture movement

To model the water regime of the soil, the simplified Richards equation is used:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[D(\theta)\frac{\partial\theta}{\partial z}\right] - S(\theta)$$

Where is:

θ - volumetric soil moisture,

D(θ) is the coefficient of moisture diffusion,

S(θ) is the moisture consumption of plants,

z - depth,

t is time.

In addition, a discrete model was used to estimate the change in humidity in the controlled layer:$0 \le z \le h$

$$\theta(t + \Delta t) = \theta(t) + \frac{Q(t) - ET(t) - D(t)}{h}$$

Where is:

Q(t) is the volume of water supplied,

ET(t) - transpiration,

D(t) - drainage,

h is the depth of the monitored layer.

4.2 Irrigation control algorithm

- Measurement: Obtaining θt from three soil levels.
- Condition assessment:
  - If → turn on watering. $\theta_t < \theta_{min}$
  - If → turn off watering. $\theta_t < \theta_{min}$
- Calculation of the volume of water supply:

$Q = (\theta_{target} - \theta_t) \cdot h \cdot \rho$

where ρ is the density of the soil.

- Valve activation and feedback control.

4.2.1 Irrigation control algorithm (step-by-step)

Step 1: Measurement of current soil moisture ()θ_t

Automatic moisture measurement is carried out on three soil levels: upper (10 cm), middle (30 cm), lower (50 cm) using contact moisture meters.

Step 2: Comparison with threshold value (θ_{min})

The measured θt values are compared with the minimum allowable moisture level set for the crop and soil type.θ_{min}

Step 3: Decision-making: $\theta t <$ θ_{min}?

If so, → go to step 4.

If not, → proceed to step 7 (waiting for the next cycle).

Step 4: Turning on the irrigation system

Valve or pump actuators are automatically activated.

Step 5: Calculation of water volume *(V)*

The volume of water supplied is calculated according to the formula:

$V - S \cdot h \cdot k.$

Where is:

S is the irrigation area,

h is the depth of moisture,

k is the correction factor for soil type and climate.

Step 6: Water management

Valves are opened, the system monitors water consumption and watering time until the required level of humidification is reached.

Step 7: Waiting (pause)

The system enters standby mode until the next control measurement at a preset time interval (e.g., 1 hour or 6 hours).

Step 8: Loop End / Restart

If the humidity level is reached, the cycle is complete.

Then the cycle starts again on a timer or with an external trigger (for example, according to a schedule or when the air temperature changes).

4.2.2 Flow diagram of the irrigation control algorithm

Beginning

- Algorithm Launch → [Start]

Process

1. **Measuring Current Soil MoistureUnit Type:**

Process→ "Measure θt (Moisture) at 3 Depths"

2. **Comparison with threshold** θ_{min}

Block type: *Solution→ "θt <* θ_{min}*?* "

Yes → watering

3. **Turning on the Irrigation System Unit Type:** *Process→ "Open Valves"*

4. **Calculation of the required volume of water Block type:**

→"Process Calculate V = S × h × k"

5. **Water ControlUnit Type:** *Process→ "Flow and Time Control"*

6. **Waiting for Feed to Complete Block Type:**

Process→ "Wait for θt ≥ to Reach θ_{min}*"*

7. **Cycle Complete Block Type:** *End→ "Watering Complete - Go Standby"*

No → Skip watering

8. **Wait for the next measurement Block type:** *Process→" Pause - wait for the next cycle"*

9. **Loop CompleteBlock Type:** *End→ "Conditions Match - Go to Standby"*

Legend:

Block	Meaning
Process	Action, Measurement, Calculation
Start/End	Start or end point
Decision	Boolean Condition (Yes/No)

4.3 Optimization of irrigation regimes

Objective function: to minimize water consumption while maintaining humidity within a given range:

$min \sum_{t=0}^{T} Q(t)$ provided $Q_{min} \leq \theta(t) \leq \theta_{max}$

Restrictions:

The frequency of watering is no more than 2 times a day;

Preventing drainage $(Dt) = 0$).

The solution was carried out numerically by the method of gradient descent and rule logic.

Below is a table (Table-4), which shows a comparison of a contact moisture meter (prototype) and the gravimetric method.

Table 4: Comparison of Contact Moisture Meter and Gravimetric Method

Parameter	Gravimetric method	TDR Contact Moisture Meter (Experimental)
Error	±1.0–1.5 %	±1.2–1.7 %
Sensitivity	High	High
Measurement Time	1–2 hours	5-10 seconds
The need for a laboratory	Required	Not required
Automation	Impossible	possible (integration into IoT)
Repeatability	high at standard	high in calibration

The table below contains a comparative analysis between two methods for measuring soil moisture: the traditional gravimetric method (reference, laboratory) and the contact TDR moisture meter (experimental version, field, automated).

The table shows that with almost comparable accuracy, the TDR moisture meter provides significantly higher efficiency and the possibility of continuous monitoring. This makes it a particularly effective tool in precision farming and real-time irrigation management systems.

5. Discussion

The results of this study confirm the relevance of applying high-precision moisture sensors in the context of sustainable water resource management, especially in arid regions and the implementation of precision agriculture systems. The experimental data and the developed mathematical model indicate that contact TDR sensors provide reliable, sensitive, and stable monitoring of soil moisture with a high degree of accuracy.

The linear relationship observed between dielectric permittivity and volumetric soil moisture is particularly important and is consistent with the findings, which also emphasize the need for accurate sensor calibration based on soil characteristics (Zhang et al., 2021; Liu et al., 2019; Ritter et al., 2015). The coefficient of determination (R^2 = 0.96) in this study highlights the strong predictive power of the model and the appropriateness of the selected variables.

The development of an automated irrigation control algorithm based on real-time moisture values and threshold levels (e.g., 70% of field capacity) demonstrates the practical applicability of the results. This approach allows for dynamic regulation of water supply, which is particularly critical in water-scarce environments. Comparative analysis shows that the system reduces water consumption by 18–22% while maintaining stable moisture conditions in the root zone, confirming its effectiveness in both farm and industrial-scale agro-systems.

The influence of temperature, bulk density, and soil contamination on measurement accuracy was also taken into account in the mathematical model. This distinguishes the present study from earlier works, which often considered only one factor (e.g., the model of Evett et al., 2012). Accounting for these variables significantly improved model adaptability and accuracy under real field conditions.

The graphical results visually confirm the consistency of measurements, showing linear or quasi-linear trends, which is important for setting algorithm thresholds. The sensitivity range of the sensors (21–28% volumetric moisture) coincides with the active water uptake zone for most crops, making the proposed system especially valuable for agroecological applications.

Thus, the main goal of the study—to develop and justify a technological solution for precise soil moisture control in irrigation systems—has been successfully achieved.

Key challenges addressed include:

- Ensuring high accuracy and repeatability of measurements;
- Adapting the model to real soil conditions;
- Developing an irrigation control algorithm based on sensor data;
- Optimizing water consumption.

It is also worth noting that the proposed approach has the potential for integration with broader automation systems, such as IoT solutions, wireless sensor networks, and mobile monitoring platforms, in line with modern trends in agricultural research (e.g., Jacobs et al., 2017; Nogueira et al., 2020).

5.1 Impact of Accuracy and Stability on Irrigation Decision-Making

High metrological performance of the sensors enables:

- Minimization of over-irrigation – preventing nutrient leaching and salinization.
- Adaptive water delivery control – enabling real-time valve and pump operation.
- Scientific justification for irrigation norms – based on actual soil moisture data.
- Consideration of spatial heterogeneity – using multi-point sensors to differentiate irrigation zones.
- Improved resource efficiency – reducing water consumption by 15–22% without yield loss.

6. Novelty And Practical Significance

- This is the first comprehensive evaluation of the accuracy, sensitivity, and stability of contact TDR moisture sensors under drip irrigation in the arid climate of Uzbekistan.
- An adaptive irrigation control algorithm using threshold values (70–90% field capacity) is proposed.
- Regression equations and statistically validated mathematical models were developed.
- The integration potential of moisture sensors with IoT and automation systems was confirmed, demonstrating water savings of up to 28.6%.

7. Conclusion

This study confirms that the use of high-precision contact moisture sensors based on soil dielectric properties is an effective and scientifically justified approach to water resource management in agricultural systems. Specifically, the following conclusions were drawn:

- The developed soil moisture monitoring system demonstrated high measurement accuracy, with a permissible deviation of no more than ±1.5% volumetric moisture, accounting for the effects of temperature, density, and contamination. This is supported by a high coefficient of determination (R^2 = 0.96) and F-statistic values that greatly exceed critical thresholds, confirming model adequacy.
- The established regression relationships (between moisture and dielectric permittivity, temperature, density, and contamination level) support the creation of adaptive irrigation control algorithms, ensuring reliable system performance under changing agroecological conditions.
- Experimental data on moisture distribution under drip irrigation showed that the bulk of moisture accumulates at depths of 20–30 cm, which corresponds to the root zone of most crops. This demonstrates the effectiveness of targeted water delivery and the relevance of moisture control at this depth.
- Comparative analysis with the gravimetric method showed that TDR sensors provide comparable accuracy while greatly outperforming in response speed, automation potential, and suitability for field conditions—making them indispensable in digital farming and smart irrigation systems.
- The developed irrigation algorithm ensures automatic decisions on turning water supply on/off based on real-time moisture data and predefined thresholds (e.g., 70% field capacity). Its application led to a 18–22% reduction in water consumption without impairing plant hydration.
- Integration of the model with digital platforms (e.g., IoT, wireless sensor networks) enables continuous monitoring, prediction, and optimization of water use—addressing global goals of sustainable water use and conservation.

Thus, the objective of this study—development and scientific justification of a precise measurement and automatic control system for soil moisture—was fully achieved. The results are of practical value for precision agriculture and can be scaled for different climate zones and soil-hydrological conditions.

7.1 Limitations and Future Research

This study is limited to the soil and climatic conditions of the Khorezm region. Future research may focus on adapting the model to other soil types, developing multi-level sensor systems, and integrating with remote sensing technologies and meteorological analysis.

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