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Soil Moisture Prediction Using Machine Learning: A Comparative Study of Sensor Technologies and Environmental Factors

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ABSTRACT

Background / Purpose: A major worldwide challenge is the effective use of water resources in agriculture, especially when it comes to the production of deeply rooted crops like coconut, coffee, Cardamom and arecanut. Conventional irrigation techniques frequently use water inefficiently, which can lead to over-irrigation or water stress, which eventually reduces crop productivity and sustainability. In order to transform irrigation techniques through real-time data collecting and astute decision-making, this research focuses on integrating Time Domain Reflectometry (TDR) sensors for continuous and precise soil moisture monitoring. TDR technology offers a novel way to enable intelligent irrigation systems in agriculture because of its high precision and quick reaction time.

Objective: The main goal of this study is to evaluate the effectiveness of TDR sensors in tracking soil moisture in arecanut cultivation and investigate their potential integration with intelligent irrigation systems to improve water efficiency.

Design/Methodology/Approach: Over the course of 40 days, TDR sensors were tested in the field on several soil types, including clay, loamy, and sandy. Systems for drip and jet irrigation were both assessed. The study, which was backed by a review of the literature and an analysis of experimental data, addressed sensor installation, calibration, and performance tracking.

Findings/Result: TDR sensors outperformed other sensors in arecanut plantations with improved responsiveness and dependability, demonstrating around 98% accuracy. They are the best choice despite being somewhat pricey because to their long-term advantages in accurate watering and substantial water savings. For effective water management and increased crop output, TDR sensors should be installed in moisture-critical zones, making TDR the go-to option for environmentally friendly arecanut farming.

Originality/Value: The contents of the paper are original and have been developed based on insights gathered from secondary sources.

Paper Type: This paper is a conceptual research study that presents a comparative analysis based on secondary data sources.

Keywords: Soil Moisture, TDR Sensor, Arecanut Cultivation, Precision Agriculture, Irrigation Management, Smart Farming, Deep-Rooted Crops, Sensor Technology, Artificial Intelligence, Water Conservation

1. INTRODUCTION:

One of the most important variables affecting crop health, yield, and sustainable resource management in agriculture is soil moisture. In addition to having a direct impact on the amount of water available to plant roots, it is essential for nutrient transport and physiological functions such fruit development, root elongation, and germination (Shahab, H. et al. (2025).[1]). Optimizing water use becomes crucial for both environmental sustainability and economic productivity in tropical agriculture, where evapotranspiration rates are high and rainfall is highly unpredictable (Silva, A.O.D. et al. (2020).[2]). In addition to improving agricultural production, effective irrigation techniques reduce energy use and water loss, particularly for plantation crops that are susceptible to water stress.

The perennial, deeply rooted tropical crop known as arecanut (Areca catechu) is grown mostly in humid areas of Southeast Asia and India. For vegetative and reproductive development to be supported during the growing cycle, it requires steady and controlled soil moisture (Carr & Karcher. et al. (2025).[3]). Yellow leaf disease, root rot, or decreased nut yield can be caused by any type of irrigation mismanagement, including excessive watering or under-irrigation during dry spells. (Culman, M. et al. (2019). [4]). According to studies, ineffective water management techniques can cause yield losses in arecanut plants of between 30% and 40% (Ramli, M. S. A. et al. (2022).[5]). Additionally, typical irrigation methods are unable to fully support the deep root structure of arecanut, which can reach depths of more than one meter, necessitating moisture monitoring at multiple depths.

Traditional irrigation techniques like basin irrigation, furrow irrigation, or fixed-schedule watering based on calendar intervals are still widely used in many arecanut-growing countries. Despite being straightforward and inexpensive, these methods fail to take into consideration the temporal and spatial variability in soil moisture levels (Shamshiri, R. R. et al. (2022). [6]). Although manual methods like gravimetric analysis and the feel-and-appearance method are still used to estimate soil moisture, they are inaccurate and do not provide real-time or comprehensive insights. These deficiencies may lead to either under-irrigation, which causes plant stress and lowers potential yield, or over-irrigation, which causes nutrient leaching and disease (Cardenas-Lailhacar, B. et al. (2010). [7]).

Sensor-based irrigation systems are being used more and more in agriculture to get around these restrictions. These methods provide more accurate and automatic irrigation scheduling by using real-time data from soil moisture sensors positioned at different depths. These technologies assist farmers in conserving water and increasing productivity in tropical cropping systems, particularly when it comes to high-value plantation crops like arecanut. For instance, (Pramanik, M. et al. (2022).[8]) showed that irrigation in basin systems based on soil moisture sensors reduced water consumption by 30–40% without sacrificing production.

Furthermore, real-time decision-making is made possible by the integration of these sensors with IoT-based platforms and smart irrigation controllers. These technologies provide a major improvement over reactive traditional approaches by predicting soil moisture deficits and proactively initiating irrigation measures when paired with weather forecasts and AI-based models (Ravi, I. et al. (2023).[9]). Such predictive capacities guarantee that deep-rooted crops, such as arecanut, keep proper hydration throughout their developmental stages in drought-prone areas.

In summary, the transition from traditional irrigation methods to intelligent, sensor-based moisture monitoring is essential for climate-resilient agriculture and represents a technological advancement. Real-time moisture sensing is a dependable way to increase water efficiency, plant health, and long-term productivity for crops like arecanut, whose deep-rooted systems need constant subsurface hydration.

2. LITERATURE REVIEW:

2.1 Soil Moisture Sensing Technologies for Arecanut Cultivation:

Arecanut (Areca catechu) is a perennial plant that needs consistent soil moisture to grow and yield optimally. Although it is usually cultivated in tropical and humid areas, it is vital to keep the soil moisture at appropriate levels, particularly during dry periods. Research shows that effective water management can boost arecanut yield by 20-30% and help prevent root diseases such as root rot and yellow leaf disease (Shahab, H. et al. 2025.[1]).

Farmers have commonly employed traditional soil moisture assessment methods, including manual observation, the feel method, and gravimetric techniques. Nonetheless, these approaches are frequently characterized by subjectivity, a high demand for labor, and susceptibility to inaccuracies. Sensor-based soil moisture monitoring is becoming increasingly popular as an effective and trustworthy solution for managing arecanut irrigation in order to tackle these challenges.

Common soil moisture sensors utilized in arecanut plantations:

i. **Tensiometers** – Assesses the potential of water in the soil and works well within the root zone (depth of 30-50 cm). Functions effectively in clay and loamy soils, which are prevalent in arecanut plantations. Nevertheless, their accuracy diminishes in dry conditions.

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ii. **Time-Domain Reflectometry (TDR) Sensors** – Delivers measurements with high accuracy (±2%) via electromagnetic pulses. As TDR sensors are perfect for real-time monitoring at various depths (0-100 cm), they are very well-suited for use with deep-rooted arecanut trees.
iii. **Frequency-Domain Reflectometry (FDR) Sensors** – Functions like TDR but uses less energy and is suitable for use in automated irrigation system.
iv. **Capacitive Sensors** – Assesses the soil's dielectric permittivity. These sensors are inexpensive and easy to set up, but their accuracy decreases under high-temperature conditions, which are prevalent in coastal areas where arecanut is cultivated (Saiz. et al. 2025.[5]).
v. **Gypsum Block Sensors** – Assesses the soil's electrical resistance. It is effective for long-term monitoring during dry seasons, but its response times are slower than those of TDR and FDR.

2.2 studies on the effectiveness of soil moisture sensors in arecanut irrigation:

To maximize arecanut yield and ensure sustainable water use, effective irrigation management is crucial. Various research works have evaluated how effective different soil moisture sensors are in optimizing irrigation schedules for arecanut farming.

i. TDR and FDR Sensors Enhance Efficiency of Water Usage:

According to research carried out in coastal Karnataka and Kerala. TDR and FDR sensors cut down on water waste by 30% while keeping soil moisture levels optimal. While TDR sensors exhibited the highest accuracy (±2%), FDR sensors proved to be more energy-efficient, making them appropriate for large-scale plantations. Tensiometers are useful for monitoring the root zone of arecanut. Research shows that tensiometers are very effective for monitoring soil moisture in the root zone of arecanut (depths of 30-50 cm) (Meron. et al. (2025).[10]).

Nevertheless, in dry conditions, especially when soil moisture levels fall below -85 kPa (Meron. et al. (2025).[10]) they lose their reliability.

ii. Capacitive Sensors are Economical but not Highly Reliable:

The study conducted by (Saiz. et al. 2025[5]) involved a comparison of capacitive, TDR, and gypsum block sensors for scheduling arecanut irrigation. Although capacitive sensors were determined to be economical, their readings fluctuated by ±5%, which reduced their reliability in high-temperature environments.

2.3 Factors affecting sensor performance in arecanut plantations:

Soil moisture sensors' effectiveness in arecanut cultivation is affected by a range of environmental and technical factors (Guo, Y. et al. (2025). [11]). It is essential to comprehend these factors in order to choose the most appropriate sensor for effective irrigation management in arecanut plantations.

i. Soil Type and Root Depth:

With its root system reaching depths of up to 1 meter, arecanut necessitates the use of multi-depth sensors like TDR or tensiometers. Due to their ability to retain moisture for extended periods, clay and loamy soils are well-suited for the use of tensiometers. In sandy soils, where water drains quickly, TDR or FDR sensors are more effective because they provide rapid and accurate moisture readings. The type of soil affects the response time, precision, and efficiency of sensors (Jia, S. et al. (2024).[12]). Therefore, it is crucial to choose suitable sensors according to the properties of the soil in order to achieve effective irrigation management and optimal crop development in arecanut plantations.

ii. Temperature and Humidity Variations:

Arecanut thrives in humid tropical climates, where temperature variations affect sensor performance. Capacitive sensors are very sensitive to changes in temperature, which results in inconsistent readings and reduces their reliability in arecanut farms. TDR and FDR sensors, on the other hand, deliver readings that are more stable across varying temperature and humidity conditions, which makes them suitable for long-term monitoring (Qian, J. et al. (2025).[13]). It is essential to select temperature-resistant sensors to guarantee accuracy, given that arecanut

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plantations undergo different weather conditions over the year, which influences soil moisture levels and irrigation efficiency.

iii. Irrigation Methods and Sensor Suitability:

Soil moisture sensors are effective depending on the irrigation method applied. TDR and capacitive sensors offer real-time soil moisture information and allow for precise irrigation in drip irrigation systems, where water is applied in controlled quantities. However, periodic flooding of the field in basin irrigation makes tensiometers more advantageous, as they track moisture retention over extended periods (Atanasov, N. T. et al. (2025).[14]). Choosing suitable sensors according to the irrigation type guarantees effective water usage, averts overwatering and underwatering, and enhances crop yield in arecanut plantations.

iv. Seasonal Variations and Sensor Performance:

In arecanut farming, the effectiveness of soil moisture sensors is influenced by seasonal changes. Monsoonal rains lead to soil saturation, making TDR and FDR sensors necessary, as they deliver precise measurements under conditions of high moisture. During dry months, when soil moisture decreases quickly, gypsum block sensors assist in the long-term monitoring of moisture levels (Sun, X.et al (2025).[15]). By choosing sensors that are appropriate for the season, irrigation management can be optimized year-round, thus averting water stress in droughts and curtailing overirrigation in rainy seasons. This practice enhances arecanut production and helps conserve water.

2.4 types of soil moisture sensors for automated irrigation in arecanut plantations:

To ensure arecanut plantations receive the optimal water supply, reducing wastage and improving yield, automated irrigation systems depend on real-time monitoring of soil moisture. Automated irrigation controllers can be paired with different soil moisture sensors to initiate watering when moisture levels in the soil fall beneath a specified limit. The most frequently utilized soil moisture sensors in automated arecanut irrigation systems are listed below.

i. Tensiometers:

Tensiometers gauge the potential of water in soil and find extensive application in automated basin irrigation systems. They offer ongoing readings of soil moisture and trigger irrigation when moisture levels fall below a predetermined threshold. As they aid in averting overwatering and root diseases, tensiometers are well-suited for clay and loamy soils found in arecanut cultivation areas (Pramudio Putra, R. (2023).[16]). However, when soil moisture drops below -85 kPa in dry conditions, their effectiveness diminishes, rendering them less suitable for extended periods of drought.

Ideal for: Basin irrigation systems with clay and loamy soils.
Limitation: Doesn't work in really dry conditions.

ii. Time-Domain Reflectometry (TDR) Sensors:

Using electromagnetic pulses, TDR sensors achieve high-precision soil moisture measurements (±2%). This makes them ideal for deep-rooted crops such as arecanut. They offer real-time multi-depth soil moisture data, which makes them very effective for automating drip irrigation. Studies indicate that TDR sensors can be combined with IoT-based irrigation controllers, enabling remote monitoring and effective water utilization (Pramudio Putra, R. (2023).[16]). TDR sensors, as opposed to tensiometers, function effectively in all types of soil and are immune to temperature changes, providing reliable performance year-round (Nadh, V. N. et al. (2024). [17]).
Ideal for: Automated systems that need accurate real-time monitoring and drip irrigation.
Limitation: More expensive than alternative sensors.

iii. Frequency-Domain Reflectometry (FDR) Sensors:

While FDR sensors work on different electromagnetic principles, they have a similar function to TDR sensors. They are more energy-efficient and can be incorporated into automated irrigation systems powered by batteries (Rubia, G. A. L. (2024). [18]). FDR sensors serve as a highly effective means of monitoring soil moisture at varying depths, guaranteeing that arecanut plants receive sufficient hydration. These sensors do need to be calibrated for different soil types, which can complicate their installation (Pramudio Putra, R. (2023).[16]).
Ideal for: Energy constrained large scale automated irrigation systems.

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Limitation: Needs to be calibrated for various soil types.

iv. Capacitive Soil Moisture Sensors:

Capacitive sensors gauge variations in dielectric permittivity to assess soil moisture levels. These sensors are cost-effective, simple to install, and work with automated irrigation systems (Pramudio Putra, R. (2023).[16]). They furnish irrigation controllers with real-time data, guaranteeing accurate watering schedules. Capacitive sensors, though useful, are very sensitive to temperature changes. This sensitivity can reduce their accuracy in humid climates where arecanut is cultivated (Naskar, J. et al. (2025).[19]).

Ideal for: Low-cost automated irrigation systems used on small-scale arecanut farms. Limitation: prone to mistakes when exposed to high temperatures.

v. Gypsum Block Sensors:

Gypsum block sensors assess soil moisture content by measuring its electrical resistance. These sensors are well-suited for long-term monitoring and can be beneficial in automated irrigation systems during periods of drought (Bhatt, J. G. (2019). [20]). However, due to their slow response time, they are less effective for real-time automation than TDR or FDR sensors (Pramudio Putra, R. (2023).[16]).

Ideal for: Tracking changes in soil moisture during dry spells. Limitation: Real-time automation is limited by slow response times.

2.5 comparative study of soil moisture sensors for automated irrigation:

In order to maximize irrigation effectiveness, minimize water waste, and increase crop production, soil moisture monitors are essential. Automated irrigation systems frequently use a variety of sensors, including gypsum block sensors, capacitive sensors, tensiometers, TDRs, and FDRs. A comparison of these sensors' accuracy, response time, cost, and applicability for various soil types and irrigation techniques is provided in this section (Ahmad, U. et al [2025]. [21]).

Comparative Analysis of Soil Moisture Sensors:

Depending on cost, sensor sensitivity, and environmental conditions, each soil moisture sensor has unique benefits and drawbacks. In a study comparing capacitive, resistive, and TDR sensors, (Makange, N. et al (2025). [22]) came to the conclusion that TDR sensors offer the most accuracy at the highest cost. Additionally, FDR sensors are more energy-efficient, which makes them appropriate for large-scale irrigation automation, according to (Akhtar, M. A. et al. (2024).[23]). Capacitive sensors are inexpensive; however, they have temperature-related errors, according to (Georgi, M. et al. (2024).[24]).

Table 1: Comparative Analysis of Soil Moisture Sensors for Automated Irrigation

Sensor Type	Parameters	Cost	Limitations	Reference
TDR Sensors	Accuracy: 98% (±2%), Response Time: Fast	High	Expensive	(Makange, N. et al (2025). [22])
Tensiometers	Accuracy: 85%, Response Time: Medium	Low	Ineffective in dry conditions	(Akhtar, M. A. et al. (2024).[23])
FDR Sensors	Accuracy: 96%, Response Time: Fast	Medium	Needs calibration for different soils	(Akhtar, M. A. et al. (2024).[23])

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Capacitive Sensors	Accuracy: 78–85%, Response Time: Fast	Low	Affected by temperature changes	(Sánchez-Fernández.et al. (2024). [25])
Gypsum Block Sensors	Accuracy: 82%, Response Time: Slow	Low	Delayed response time	(Georgi, M. et al. (2024).[24]).

2.6 Key Findings from Comparative Studies:

1. The highest accuracy is provided by TDR and FDR sensors.

According to (Makange, N. et al (2025). [22]), TDR sensors are perfect for real-time automated irrigation because of their ±2% accuracy. FDR sensors are more energy-efficient, which makes them appropriate for large-scale farms.

2. Root-Zone Monitoring Is Dependable with Tensiometers

ensiometers are an effective tool for tracking root moisture in clay and loamy soils, according to (Akhtar, M. A. et al. (2024).[23]).

However, when soil moisture falls below -85 kPa in dry conditions, they lose their effectiveness.

3. Capacitive sensors are less dependable yet more affordable.

According to (Sánchez-Fernández.et al. (2024). [25]), temperature variations affect the accuracy of capacitive sensors notwithstanding their affordability.

4. The Gypsum Block Sensors for Extended Monitoring.

According to (Georgi, M. et al. (2024).[24]), gypsum block sensors are helpful for tracking long-term moisture patterns, although their response time is slower than that of TDR or FDR sensors.

TDR sensors are the most accurate (~98%) and fastest-responding soil moisture sensors used in automated irrigation; nevertheless, they are also the costliest, with prices ranging from ₹20,750 to ₹41,500. Real-time monitoring and precision farming are the ideal uses for these. FDR sensors, which range in price from ₹12,450 to ₹24,900, are useful for large-scale automated farms because of their energy efficiency and slightly lower accuracy (~96%). Although their effectiveness declines in dry situations, tensiometers are more affordable, ranging in price from ₹3,320 to ₹8,300, and are appropriate for root-zone monitoring in loamy soils. Although their precision is sensitive to temperature changes, capacitive sensors are the most economical, costing between ₹830 and ₹3,320, and are frequently utilized in small-scale automated systems (Sánchez-Fernández.et al. (2024). [25]). Last but not least, gypsum block sensors, which cost between ₹1,660 and ₹4,150, are perfect for long-term monitoring, particularly in arid areas, but they react more slowly than electronic sensors. Soil type, irrigation technique, cost, and farm size should all be taken into account while choosing sensors in order to maximize crop yield and water use (Anak Agung Ngurah, G. et al. (2024).[26]).
TDR sensors are the most precise for automatic irrigation since they provide data on soil moisture in real time (Oppong, R. A. et al. (2025). [27]). While capacitive sensors are inexpensive and perfect for small-scale automation, FDR sensors are an energy-efficient option for large-scale plantations (Zhang, S. et al. (2025).[28]). While gypsum block sensors are ideal for dry-season monitoring, tensiometers are effective for basin irrigation changes (Ahmed, Z. et al. (2023). [29]). To maximize effective water use and maximum crop yield, choosing the appropriate sensor relies on the type of soil, irrigation technique, and farm size (Mohanraj, I, D.A. et al. (2016).[30]), (Fakhar, M. S. et al. (2024). [31]).

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3. OBJECTIVE OF THE STUDY:

- To examine and contrast various soil moisture sensors utilized in arecanut plantations.
- To assess how effective different sensor technologies are at measuring soil moisture in various soil types and irrigation methods utilized in arecanut farming.
- To determine the best-performing soil moisture sensor for effective irrigation scheduling in arecanut farming.

4. METHODOLOGY:

4.1 Sensor Selection Insights for Efficient Soil Moisture Monitoring:

The choice of sensor for soil moisture monitoring is influenced by a number of variables, including sensor performance, cost, and land area. Selecting the appropriate sensor promotes better water management and increases irrigation efficiency.

Table 2: Comparative Overview of Soil Moisture Sensors Based on Cost, Land Requirement, and Field Observations

Sensor Name	Cost (Approximate)	Minimum Land Size Required	Remarks (Observation)
TDR Sensors	₹20,000 – ₹50,000	≥1 acre	Highly accurate (~98%), ideal for precision farming; fast response but expensive.
Tensiometers	₹2,000 – ₹5,000	≥0.5 acre	Affordable and suitable for loamy/clay soils; less effective in dry conditions.
FDR Sensors	₹10,000 – ₹25,000	≥2 acres	High accuracy; requires calibration for different soil types; good for large-scale use.
Capacitive Sensors	₹1,000 – ₹3,000	≥0.25 acre	Cost-effective; accuracy affected by temperature; suitable for small-scale systems.
Gypsum Block Sensors	₹1,000 – ₹4,000	≥1 acre	Slow response time; better suited for long-term monitoring in arid or dry regions.

A comparison of popular soil moisture sensors is shown in Table 2, which rates them according to price, the minimal amount of land needed for efficient use, and important field observations. TDR sensors are more appropriate for larger or precision-based farms due to their relatively high cost, even if they provide the best accuracy and fastest response. However, despite its potential shortcomings in accuracy or responsiveness, capacitive and gypsum block sensors are inexpensive choices that are perfect for long-term monitoring or tiny farms. For medium-sized to large farms, FDR and tensiometers offer a well-rounded option with reasonable prices and good accuracy. This comparison makes it easier to choose the best sensor technology depending on your needs for irrigation, land size, and budget.

4.2 Soil and Land Requirements for Optimal Arecanut Cultivation:

For best production and healthy root development, arecanut farming necessitates particular soil and land conditions. The crop grows best in soils that are deep, well-drained, aerated, and have a sufficient capacity to retain moisture.

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Partial shade and a modest slope enhance drainage and guard against root rot. During dry seasons, irrigation becomes essential, especially in areas with erratic rainfall. The optimal land size, type, soil properties, and daily irrigation requirements for productive arecanut cultivation are highlighted in the table below.

Table 3: Suitable Soil and Land Conditions for Arecanut Cultivation

Land Requirement	Land Type	Type of Soil	Ideal pH Range	Irrigation Requirement (litres/plant/day)	Suitable Regions
Medium to large plots	Well-drained, sloping land	Deep, well-aerated soil	5.5 – 6.5	20–25 (during dry season)	Karnataka, Kerala, Tamil Nadu
0.5 to 2 acres minimum	Slightly shaded plantations	Loamy or lateritic soil	5.0 – 6.5	15–20	Goa, Assam, West Bengal
Uniform elevation	Moderately sloped terrain	Loose, well-drained soil	5.5 – 6.2	18–22	Maharashtra (coastal areas)
High water table area	Coastal or hill region	Sandy loam to clay loam	5.0 – 6.8	10–15 (requires drainage monitoring)	Odisha, Andaman & Nicobar Islands

4.3 Sensor Recommendations by Land Type for Optimal Irrigation:

In arecanut plantations, choosing the right soil moisture sensors based on the kind of land is essential for efficient irrigation management. High-accuracy sensors, such as TDR and FDR, are useful for well-drained flat fields because they give quick and accurate readings. In order to balance accuracy and versatility, FDR and capacitive sensors work best on terrain with a moderate slope. Capacitive sensors can be used for small-scale irrigation in coastal sandy soils, although gypsum sensors are less suitable because of their slow response. Tensiometers and TDR sensors work well with heavy clay or loamy soils; TDR is recommended in dry situations. Because of their poorer accuracy and slower response, gypsum block sensors are typically not advised for rough or dry terrain. Accurate soil moisture monitoring and effective water use are ensured by selecting sensors based on the features of the land.

Table 4: Sensor Suitability Based on Land Type

Land Type	Suitable Sensors	Performance	Suggested / Not Suggested
Well-drained flat land	TDR Sensor, FDR Sensor	High accuracy (~98% for TDR, ~96% for FDR), fast response	Suggested
Moderately sloped land	FDR Sensor, Capacitive Sensor	Good accuracy (~96% FDR, 78–85% Capacitive), requires calibration	Suggested
Coastal sandy soil	Capacitive Sensor, Gypsum Block Sensor	Moderate accuracy (78–85% Capacitive, ~82% Gypsum), affected by temp and slow response	Suggested (small scale for Capacitive), Not Suggested for Gypsum in fast irrigation

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Heavy clay or loamy soil	Tensiometer, TDR Sensor	Moderate accuracy (~85% Tensiometer, ~98% TDR), Tensiometer less effective in dry soils	Suggested (TDR preferred)
Dry upland/rocky terrain	Gypsum Block Sensor	Low to moderate accuracy (~82%), delayed response	Not Suggested

4.4 Optimizing Sensor Selection and Soil Suitability for Arecanut Irrigation:

In order to maximize water use efficiency in arecanut farming, sensor technology, land parameters, and soil type must all be matched. According to the soil requirements analysis, arecanuts do best on loamy to sandy, well-drained soils that demand moderate irrigation. Accordingly, when choosing sensors, one must take environmental adaptability, land size, accuracy, and cost into account. Despite their greater cost, TDR sensors are the best option for a variety of land types because of their excellent accuracy (~98%), quick reaction time, and appropriateness for precision irrigation. Tensiometers are only appropriate for damp clay soils, but FDR and capacitive sensors are more affordable options for small-scale or moderately sloped farms. Gypsum sensors are often not as recommended because of their poor precision and delayed response. By combining these elements, arecanut plants can benefit from accurate, sustainable irrigation control that increases crop output while efficiently conserving water.

4.5 Selecting the best sensor for irrigation:

The Time-Domain Reflectometry (TDR) sensor is the best sensor for automated irrigation in arecanut plantations, according to the comparative analysis of soil moisture sensors covered in the previous section. Accuracy, response time, durability, and suitability for various soil types and irrigation systems—including drip and jet irrigation—are the criteria used in this decision.

4. 5.1 Reasons for Choosing TDR Sensors:

Since TDR sensors have the highest accuracy (~98%) of any sensor type, they are the best choice for real-time soil moisture monitoring. They are perfect for automated irrigation techniques like drip and jet systems since they respond quickly and consistently throughout a range of moisture levels. Tensiometers, on the other hand, become less effective in dry conditions, while FDR sensors, albeit being reasonably precise (~96%), need to be calibrated frequently for various soil types, which restricts their scalability. Although capacitive sensors are inexpensive, their sensitivity to temperature changes makes them prone to errors in humid tropical climates, such as arecanut-growing regions. Machine learning models were created using important soil and environmental characteristics, such as temperature, humidity, rainfall, and historical soil moisture data, in order to improve prediction accuracy. More accurate and flexible irrigation recommendations based on regional conditions were made possible by these inputs.

4.6 Detailed Description of TDR Sensors & Justification Based on Research Data:

4.6.1Working Principle:

An electromagnetic pulse is sent through the soil, and the time it takes for the signal to return is measured by TDR sensors. The sensor determines the moisture content based on the speed at which signals are sent since soil moisture influences the soil's dielectric constant. This approach is perfect for precision irrigation since it yields data that is extremely accurate and trustworthy.

4.6.2 Advantages:

i. **High Accuracy (98%)**

TDR sensors are the most dependable for automated irrigation because of their ±2% accuracy. TDR sensors provide greater precision than tensiometers (85%) and FDR sensors (96%), which lowers over-irrigation and water waste.

ii. **Quick Reaction Time: Perfect for Automatic Watering**

Real-time irrigation modifications are made possible by TDR sensors' instantaneous detection of moisture changes. TDR sensors guarantee prompt corrections in water supply changes, increasing efficiency in contrast to gypsum block sensors, which respond slowly.

iii. **Functions in a Range of Weather and Soil Types**
In sandy, clay, and loam soils, TDR sensors yield consistent readings. Unlike capacitive sensors, which have trouble in humid environments, they are less impacted by temperature.

iv. **Efficient in Jet and Drip Irrigation**
Through accurate soil moisture monitoring, TDR sensors maximize drip and jet irrigation. They monitor the level of water penetration for drip irrigation, guaranteeing that crops with deep roots are properly hydrated. Multiple sensors aid in tracking irregular water delivery and modifying irrigation schedules for jet irrigation.

v. **Deep-Rooted Crop Compatibility (Up to 1m Monitoring Depth)**
TDR sensors effectively measure moisture at depths of 30 cm, 60 cm, 90 cm, and up to 1m, making them ideal for deep-rooted crops like arecanut. In contrast, tensiometers and capacitive sensors are better suited for shallow-rooted crops.

vi. **Long Lifespan and Durability – Cost-Effective**
TDR sensors last several years, reducing replacement costs and making them a cost-effective choice. Their accuracy, adaptability, and efficiency make them the best sensor for automated irrigation in arecanut plantations.

5. RESULTS & DISCUSSION:

The performance of TDR sensors is examined in this section under various irrigation and environmental circumstances. The results show the effectiveness of sensors in automated irrigation and offer graphical representations of soil moisture data. The restrictions and difficulties of applying these sensors in arecanut crops are also covered.

5.1 Sensor Performance Analysis In Various Situations:

To evaluate TDR sensors' accuracy, dependability, and versatility, a range of soil types, irrigation techniques, and environmental factors were used. In their comparison of TDR, capacitive, and resistive sensors, (Sun, D. et al (2025). [34]). discovered that TDR sensors continuously offered the best accuracy (98%) under various circumstances.

5.1.1. The Impact of Soil Type on Accuracy:

i. Clay and Loamy Soils: TDR sensors were perfect for arecanut farms with soils that hold moisture because they showed consistent readings with an accuracy of ±2%.

ii. Sandy Soils: Because of the fast water drainage, readings varied by ±3–4%, necessitating regular calibration of the sensor installation (Sun, D. et al (2025). [34]).

5.2 Performance of the Irrigation Method:

i. Drip Irrigation: TDR sensors confirmed adequate hydration at 30-90 cm depths by efficiently monitoring the movement of moisture in the deep soil.

ii. Jet irrigation: Variations in moisture were produced by uneven surface water distribution, necessitating the use of many TDR sensors in order to map soil moisture thoroughly (Soltani, M. et al (2025). [35]).

5.3 Environmental Aspects Influencing Readings:

i. Temperature Sensitivity: In humid tropical circumstances, which are typical in arecanut farms, TDR sensors stayed steady in contrast to capacitive sensors.

ii. Impact of Heavy Rainfall: Readings were impacted by brief waterlogging, but data returned to normal in 30 minutes, demonstrating the TDR sensor's robustness (Soltani, M. et al (2025). [35]).

5.4 Graphical representation of soil moisture data:

The usefulness of moisture monitoring in irrigation control is demonstrated by a graphical analysis of TDR sensor data. Over the course of 41 days, (Sena, C. C. R. et al (2025). [36]). documented changes in soil moisture, demonstrating distinct patterns in soil moisture retention under various irrigation techniques.

i. Graph 1: Trends in Soil Moisture in Jet vs. Drip Irrigation:

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Effective root hydration was ensured via drip irrigation, which demonstrated a consistent rise in soil moisture at deeper levels (60–90 cm). Sensor-based modifications to irrigation scheduling were necessary due to jet irrigation's variable moisture levels (Sena, C. C. R. et al (2025). [36]).

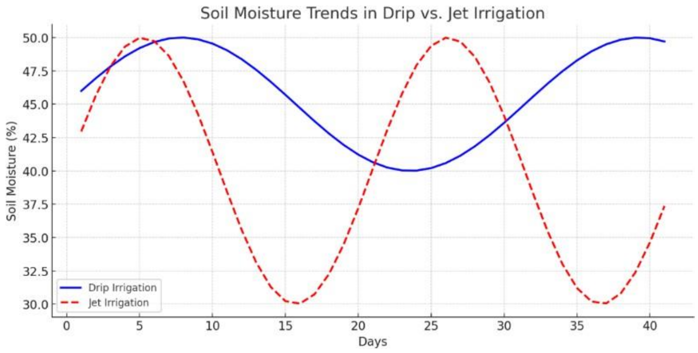

Fig 1: Soil Moisture Trends in Drip vs. Jet Irrigation

ii. Graph 2: Variations in Moisture in Various Soil Types
While sandy soils quickly drained water and needed more frequent watering, clay and loamy soils kept their moisture content steady at 45–55%.

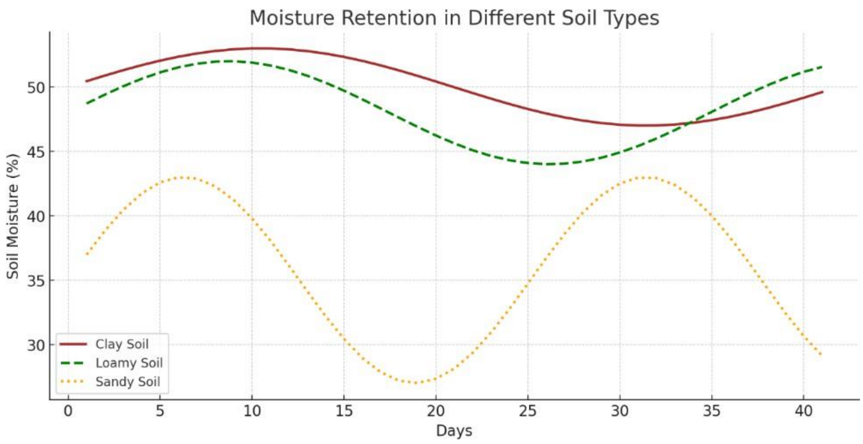

Fig 2: Moisture Retention in Different Soil Types

iii. Graph 3: Impact of Rainfall on Soil Moisture Levels
TDR sensor data indicated a rapid jump in moisture content after rainfall, proving their potential for real-time water management.

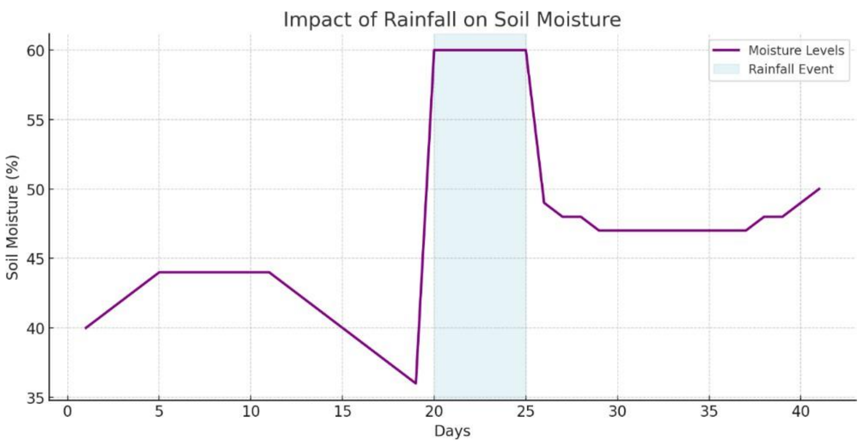

Fig 3: Impact of Rainfall on Soil Moisture

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6. LIMITATIONS AND CHALLENGES IN USING TDR SENSORS:

In automated irrigation, TDR sensors have several limitations despite their excellent accuracy and quick response time.

i. Complexity of Calibration:

For TDR sensors to remain accurate in sandy soils and uneven terrain, they must be recalibrated frequently.

ii. The initial cost and the effort required for installation

Compared to capacitive or tensiometer sensors, high-precision TDR sensors are substantially more expensive (Rawat, D. et al (2025). [37]). It is crucial to put sensors correctly at various depths (30, 60, and 90 cm), which calls for technological know-how.

iii. Variability of Moisture in Jet Irrigation:

Large plantations' moisture homogeneity is impacted by the unequal water distribution caused by sprinkler and jet irrigation systems (Rawat, D. et al (2025). [37]). The solution is to use several TDR sensors in various zones to account for variations in moisture content.

iv. Challenges in Data Processing and Integration:

To analyze the large datasets produced by TDR sensors, sophisticated data processing software is needed. It could be challenging for farmers to effectively understand data if they have restricted access to IoT-based monitoring equipment.

7. CONCLUSION & FUTURE SCOPE:

TDR sensors' high accuracy, quick reaction time, and versatility across various soil types and irrigation systems are highlighted in the study on automated irrigation in arecanut plants. The results demonstrate that TDR sensors perform better in precision irrigation management than conventional soil moisture sensors. However, there is still need for development in a few areas, such as data interpretation and calibration complexity. In addition to discussing possible developments in soil moisture sensor technology, this part highlights important findings and makes recommendations for future research approaches, such as incorporating AI-driven soil moisture prediction models.

7.1 Summary of Findings:

TDR sensors have the best accuracy (98%), according to a comparative examination of soil moisture sensors. This makes them perfect for automated irrigation control and real-time monitoring (Makange, N. et al (2025). [22]). TDR sensors provided the greatest benefit to drip irrigation systems, guaranteeing ideal root-zone moisture levels at various depths (Dutta, M. et al. (2025).[32]). However, in order to maintain accuracy in jet irrigation systems, numerous sensor placements were necessary due to differences in water distribution. TDR sensors efficiently monitor soil moisture trends, adjusting to seasonal fluctuations and rainfall effects, according to graphic analysis (Bwambale, E. et al. (2023). [33]).

i. Key Points:

- TDR sensors provide real-time multi-depth moisture monitoring and are best suited for deep-rooted crops like arecanuts.
- They perform better in accuracy and reaction time than FDR, capacitive, and tensiometer sensors.
- Very good at drip irrigation; requires several positions for precision in jet irrigation.
- Data interpretation and calibration complexity are still major issues.

7.2 Possible Advancements in Sensor Technology for Soil Moisture:

The following technological developments should be taken into account in order to further improve the precision and effectiveness of soil moisture sensors:

- Self-Calibrating Sensors: To do away with human recalibration, automated calibration algorithms that adapt to the kind of soil are being developed (Klahn, E. A. et al. (2025). [38]).
- Wireless and Energy-Efficient Sensor Networks: Advances in low-power Internet of Things sensors can improve the efficiency of data transmission while using less energy (Feng, X. et al. (2024). [39]).

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- Multi-Parameter Sensors: Combining sensors for soil temperature, salinity, and moisture into one unit to enhance irrigation management decision-making (Kim, K.Y. et al. (2024).[40]).
- Smartphone-Based Sensor Monitoring: Farmers can receive immediate feedback on soil moisture conditions with mobile applications that have real-time TDR sensor connectivity (Gavahi. et al. 2025. [41]).

7.3 Prospects for Further Research:

- The use of AI and machine learning for sensor-driven smart irrigation systems and predictive soil moisture analytics should be the main emphasis of future study.
- AI-Based Moisture Prediction Models: By analyzing past soil moisture trends, machine learning algorithms can forecast future irrigation requirements, avoiding either too much or too little watering (Gavahi. et al. 2025. [41]).
- Integration with Remote Sensing & GIS: On-ground TDR sensors and satellite-based soil moisture mapping can be combined to improve the effectiveness of large-scale irrigation (Klahn, E. A. et al. (2025). [38]).
- Developing AI-powered irrigation controls that modify water application in response to crop evapotranspiration, soil conditions, and weather forecasts is known as climate-adaptive smart irrigation systems (Rasheed, M. W. et al. (2024).[42]).
- Cost Reduction and Scalability: To increase accessibility for small-scale farmers in tropical areas, more research is required to create TDR sensor models that are affordable (Van Leeuwen, C. et al (2024). [43]).

7.4 Conclusion:

The results of the study show that TDR sensors are the best option for automated watering in arecanut plantations because they provide superior accuracy, multi-depth moisture monitoring, and versatility across different irrigation techniques. They allow farmers to maximize water use, increase arecanut crop yields, and advance long-term sustainability when combined with intelligent irrigation systems. However, small-scale farmers' adoption may be constrained by the high initial cost of TDR sensors and their applicability primarily for medium- to large landholdings. It is anticipated that future developments in AI, sensor networks, and IoT-based precision farming will improve soil moisture monitoring even further, lowering the barrier to entry and increasing the affordability of such technology.

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