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Intelligent system for automated soil moisture monitoring[1]

Sistema inteligente para monitoramento automatizado da umidade do solo

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HIGHLIGHTS:
The developed system enables precise irrigation management, optimizing water use in Oxisols and Inceptisols.
Colder temperatures are recommended for accurate automation since tensiometric measurements vary according to the temperature.
Accurate calibration curves of tensiometers optimize water use and irrigation automation.

ABSTRACT: Water application to cultivated soil is often done without careful consideration in irrigated agriculture, leading to inefficient or suboptimal water usage. In many instances, the intricate relationship between soil, water, and plants, as well as the potential and limitations of irrigation systems, is overlooked. Sustainable irrigated agriculture necessitates the development of a soil moisture monitoring system that curtails water loss and enhances overall efficiency. This study aimed to develop and assess the efficiency of an intelligent system for monitoring soil moisture. The system comprises two stations: the first collects data on apparent soil moisture parameters using sensors, while the second transmits this data to a central processing station. The system precisely determines current soil moisture values, enabling estimation of the required irrigation water volume to meet the crop's water demand based on field capacity. Results from the calibration curve of the sensors indicate that the system can measure current soil moisture precisely, aiding in irrigation management. For irrigated areas under unsaturated soil conditions, it is recommended to use tensiometers due to their higher reliability between field capacity and permanent wilting point, ensuring more accurate irrigation practices.

Key words: Arduino, soil moisture sensors systems, microcontroller, water management

RESUMO: Na agricultura irrigada, é comum a aplicação de água no solo cultivado sem critério, resultando em uso ineficiente ou não otimizado da água. Em muitos casos, a relação solo-água-planta, bem como as potencialidades e limitações dos sistemas de irrigação são ignoradas. A agricultura irrigada sustentável requer o desenvolvimento de um sistema de monitoramento da umidade do solo que evite a perda de água e melhore a eficiência do uso. O objetivo deste estudo foi desenvolver e avaliar a eficiência de um sistema inteligente de monitoramento da umidade do solo. O sistema é composto por duas estações: a primeira coleta os dados sobre parâmetros de umidade aparente do solo usando sensores, enquanto a segunda transmite esses dados para uma estação de processamento central. O sistema determina precisamente os valores atuais de umidade do solo, permitindo estimar o volume de água de irrigação necessário para atender à demanda hídrica da cultura com base na capacidade de campo. Os resultados da curva de calibração dos sensores indicam que o sistema pode medir com precisão a umidade do solo atual, auxiliando no manejo da irrigação. Para áreas irrigadas em condições de solo não saturado, recomenda-se o uso de tensiômetros devido à sua maior confiabilidade entre a capacidade de campo e o ponto de murcha permanente, garantindo práticas de irrigação mais precisas.

Palavras-chave: Arduino, sistema de sensores de umidade do solo, microcontrolador, manejo de água

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Introduction

Optimizing water use through efficient irrigation practices is crucial for sustainable agricultural development, particularly in arid and semi-arid regions where water availability is limited in quantity and quality. In this regard, effective irrigation management prevents water loss, lowers electricity costs, and enhances both crop yield and quality (Pramanik et al., 2022). Techniques include tapping into alternative water resources (Zhang & Shen, 2019; Li et al., 2020), employing methods with high water distribution efficiency (Gupta et al., 2020), and utilizing intelligent systems that provide real-time soil moisture information, thereby improving water use efficiency (Cao et al., 2020; Mohamed et al., 2021).

The utilization of new technologies in agriculture has intensified in recent years, primarily owing to the significance of implementing autonomous equipment. The real-time monitoring of soil moisture is among the most critical aspects for the success of irrigated agriculture, emphasizing the necessity to measure both the quantity and opportune moment of water application in the soil (Weiss et al., 2020; Vera et al., 2021).

Soil moisture sensing technologies serve various purposes, including precision agriculture, landscape moisture monitoring, and global soil moisture mapping. These techniques span from large-scale satellite-based remote sensing suitable for regional and global scales (hundreds of km^2) to in-field sensors for plot and field measurements ranging from 0.1 m^2 to 10,000 m^2 (Kashyap & Kumar, 2021). On the local scale, many technologies have been proposed, including neutron moderation, nuclear magnetic resonance, electrical resistance, dielectric sensors encompass capacitance sensors, frequency domain reflectometry, time domain reflectometry, amplitude domain reflectometry, and time-domain transmission sensors (Hernández et al., 2018; Sharma, 2018).

This research aimed to develop and assess the efficiency of an intelligent system for monitoring soil moisture.

Material and Methods

The research was developed at Universidade Federal Rural do Semi-Árido (UFERSA), Centro Multidisciplinar de Angicos, Angicos, RN, Brazil. The municipality of Angicos is located in the central region of Rio Grande do Norte state (5° 39' 18" S, 36° 36' 51" W, and altitude of 110 m).

The climate of the region is characterized by a hot and semi-arid climate, with a rainy period from February to April, presenting 70% of annual average relative air humidity, 2400 hours of insolation, and annual average temperatures of 33.0 °C (maximum), 27.2 °C (average), and 21.0 °C (minimum) (IDEMA, 2008). Data from the Angicos pluviometric post indicate an average annual rainfall of 530 mm, based on a historical series from 1911 to 2004.

For the development of the soil moisture monitoring system (SMMS), a design methodology was developed to meet the application and operation needs, with its main characteristic being the low associated cost (Figure 1). The sequence of the project starts with objectives to be achieved, available materials

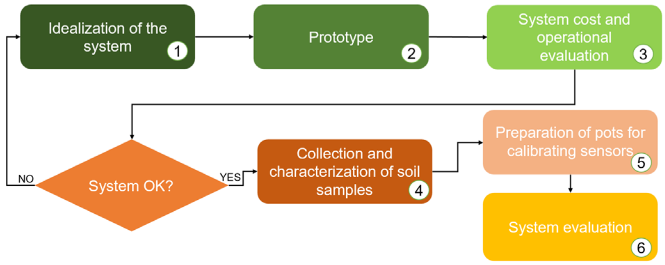


Figure 1. Methodological procedure: flowchart of the steps taken in system development

and technologies, prototype construction, cost evaluation, and system functioning. Once the low cost and applicability criteria are met, the calibration curves are obtained, following the next process steps.

SMMS consists of a data collection station (DCS) for soil moisture variables and a central data processing station (CDPS) for communicating information regarding soil moisture via the Internet (Ojo et al., 2015). Both stations are composed of an Arduino Nano V.3.0 ATMEGA 328 microcontroller, basic electronic components for their operation, and a 2.4 GHz radio transmitting antenna – module NRF24L0 to transfer data between them. This antenna offers the advantages of easily adjustable output power and its low-cost and low-power consumption characteristics. CDPS is differentiated by having a WiFi ESP8266 NodeMcu ESP-12 module connected to the internet, enabling sending moisture data to a database.

The soil moisture monitoring system can be adapted for different conditions of use and, in its processing core, it has two operating modes: (1) active mode, in which the system acts directly over-irrigation control, controlling pump activation to maintain soil moisture in the irrigated crop ideal conditions; (2) passive mode, in which the device informs the user about exact time to perform irrigation and also the moment to stop it. This second mode is used in cases where irrigation water is not always available, and the user has control over-irrigation.

To ensure SMMS efficiency and accuracy, it is necessary to calibrate the sensors on the ground where the system will work. Plastic pots were filled with soil material and then sensors were installed at a 0-0.30 m depth to calibrate the system. The soil was saturated with tap water, and then volumetric moisture measured was compared with signal emitted by sensors.

Two soil samples with different textures were collected in irrigated areas of Baixo Assú at 0-0.40 m soil layer for physical characterization (Table 1). The first sample was classified as an Oxisol, with a sandy loam texture, while the second was classified as an Inceptisol, with a sandy clay loam texture (United States, 2014), corresponding to Latossolo and Cambissolo, respectively, in the Brazilian Soil Classification System (EMBRAPA, 2018).

Sensors were calibrated through an auxiliary system called Monitoring and Data Storage Station (MDSS). The station stores data instead of transmitting it, ensuring no data loss during calibration. Three temperature sensors (DS18b20 – Dallas Semiconductor) and three tensiometers, with pressure transducers model MPX5100DP coupled, were connected to each Arduino Mega, responsible for monitoring soil moisture in the pots.

Table 1. Physical characterization of soil used in the experiment

Soil	Particle size fraction (kg kg $^{-1}$)					Density (kg dm $^{-3}$)		Textural
	Coarse sand	Fine sand	Sand	Silt	Clay	Apparent	Real	Class
Oxisol	0.27	0.57	0.84	0.05	0.11	1.48	2.50	12
Inceptisol	0.18	0.33	0.51	0.21	0.28	1.37	2.56	07

Pots were drilled at the bottom with a diameter of 0.01 m and then filled with a 0.02 m layer of gravel and TNT (non-woven fabric) geotextile blanket to prevent soil loss. After that, the pots were filled with 0.18 m of soil, and during filling, temperature sensors (DS18b20 – Dallas Semiconductor) were installed at a depth of 0.15 m from the surface. A total of six pots were used for calibration, three containing Oxisol and three containing Inceptisol.

To keep the soil more cohesive and closer to natural conditions, pots filled with soil were placed in an empty water tank and later filled with water until 1/3 of the soil height within the pots. Holes at the pots' bottom allowed the soil to be moistened by capillarity, and after 48 hours, pots were removed from the box and allowed to drain in a place protected from rain and sun.

Three weeks after removing the pots from the reservoir, tensiometers were installed, according to Azevedo & Silva (1999). The tensiometer porous capsule and soil temperature sensors were installed at 0.15 m depth. After the installation of tensiometers, all sensors were connected to MDSS and placed back into the water tank following the same procedure used to accommodate the soil. At this time, the water tank was filled with 2/3 of soil height within the pots to saturate soil samples (Figure 2A) completely.

After soil saturation, pots were covered with plastic to prevent water loss by evaporation during drainage (Figure 2B). After soil drainage was finished, pots were weighed thrice daily for 32 days to determine the sensors' calibration curve.

A.

B.

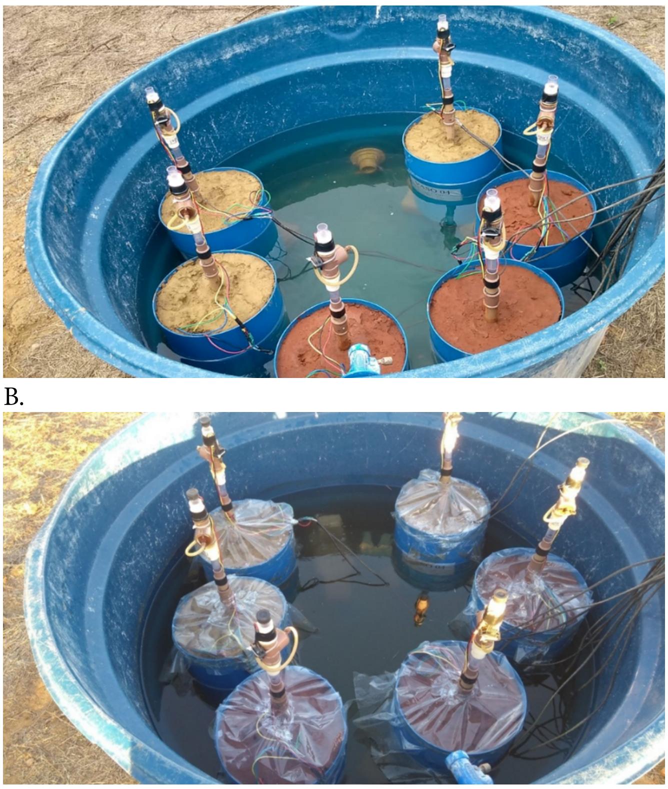


Figure 2. Detail of soil saturation process with (A) and without (B) pot cover

Scales were developed to connect to the ECD; each scale was built with two 20 kg load cells and an HX711 signal amplifier. The scales were calibrated in the laboratory using cast iron weights. The soil moisture reading on the ECD was obtained from the daily weighing of each station on digital scales with a capacity of 40 kg, connected to a panel with a microcontroller. Despite the proximity to water saturation reservoirs, care was taken during movement to the scale to prevent lateral deformation and cracking of the pots.

Calibration curves for tensiometers and moisture sensors for both studied soils were determined from the relation between the values recorded by pressure transducers (kPa) at 8:00 a.m., 12:00 p.m., and 5:00 p.m. hours, with the weight of each soil sample measured in the same period.

The results were subjected to linear regression analysis; thus, linear and angular coefficients were estimated to determine the best fit of the sensors. The Minitab statistical software was used for the analysis.

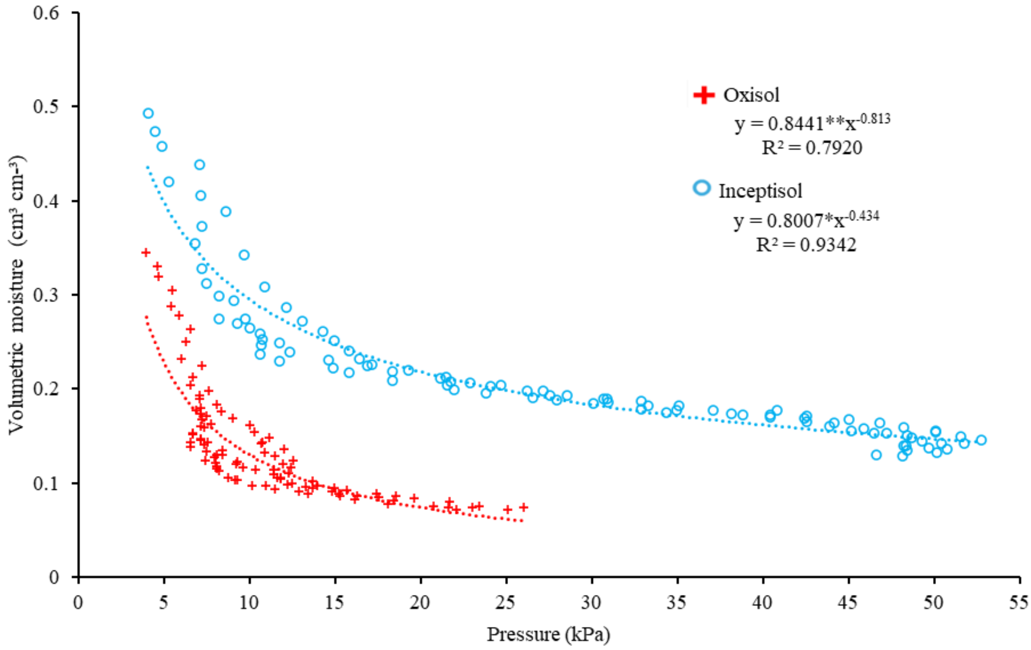
Results and Discussion

The results, which determined the calibration curves for the tensiometers in both studied soils, are presented in Figure 3. These curves were established by relating the values recorded by pressure transducers (kPa) at 8:00 a.m., 12:00 p.m., and 5:00 p.m. with the weight of each soil sample measured simultaneously.

The generated curves exhibit a strong relation, although some points deviate from the trend line, particularly at the inflection point of the curve. This inflection point corresponds to the moment the soil reaches its field capacity, as Alencar et al. (2019) indicated. In the case of Oxisols and Inceptisols soils, drainage ceased, and they reached field capacity at pressures of 10 and 15 kPa, respectively. Excess water was drained at this point, and water losses occurred gradually.

The field capacity of Oxisols is generally relatively low due to their predominantly sandy texture and high permeability. This results in a limited ability to retain water, especially after periods of heavy rainfall. Conversely, Inceptisols tend to have a moderate to high field capacity, influenced by soil texture and aggregation (Pasaribu et al., 2023).

Points situated near the trend line (Figure 3) suggest that the signals are consistent with the field capacity of the soils. This underscores the importance of using tensiometers under non-saturation conditions to ensure accurate readings between soil field capacity and permanent wilting point, as emphasized by Reichardt & Timm (2020). The coefficients of determination ($R^2 > 0.79$) observed between soil moisture readings and pressure transducer response signals attest to the accuracy of the potential model.



*, ** - Significant at p ≤ 0.05 and p ≤ 0.01 by the F test; R^2 - Coefficient of determination

Figure 3. Calibration curves of the sensors based on the volumetric moisture for two types of soils with readings at three times of the day (08:00 a.m., 12:00 p.m., and 05:00 p.m.)

Oxisols exhibit greater fluctuations in volumetric moisture content and tensiometer pressure in response to daily temperature variations due to their predominantly sandy texture and porous structure. The variations observed in Oxisols result from the interaction between their physical properties and climatic conditions, emphasizing the importance of monitoring and adjusting irrigation according to these patterns to optimize water use in agriculture (Oliveira et al., 2021; Silva et al., 2023).

The results obtained from the calibration curves indicate that the soil moisture monitoring system was satisfactory (Figure 3), serving as a potential tool to assist farmers in making decisions about irrigation management, offering the possibility of automation, and enhancing system efficiency (Arruda et al., 2017; Gupta et al., 2020). Continually monitoring soil moisture mitigates water losses and enhances water use efficiency. Fayaz et al. (2022) and Gupta et al. (2020) confirm this thesis by stating that soil moisture directly influences crop growth, climate dynamics, and water management, highlighting its importance for both agricultural productivity and ecological balance. Therefore, the operating range of sensors utilized by the monitoring system should be set between the field capacity and the critical moisture level for crop harvest.

Fluctuations in soil temperature induce minor oscillations in tensiometer measurements (Figure 4). The pressure changes recorded by the transducer arise from two assumptions. The first assumes that the expansion of tube walls increases the available space for the fluid, resulting in a decrease in internal pressure compared to atmospheric pressure. The second assumes that changes in water temperature, corresponding to an increase in environmental temperature, lead to fluid expansion. This expansion causes a hydraulic load increase, consequently resulting in a rise in pressure relative to atmospheric pressure (Jia et al., 2023).

Regarding variations in voltage signals due to temperature fluctuations throughout the day, the first stage, spanning from 6:00 a.m. to 8:00 a.m., exhibited a reduction in signal strength (Figure 4A); this decrease can be attributed to overnight cooling, which causes thermal contraction in the tensiometer components and the surrounding soil, resulting in lower pressure readings (Dainese et al., 2022). Significant reading variations occurred between 8:00 a.m. and 5:00 p.m. during the period of highest daily temperatures, with peaks of oscillations observed between 11:00 a.m. and 1:00 p.m., as noted in other stages. These fluctuations indicate the heating of both the soil and the sensor, leading to thermal expansion and subsequent variations in the internal pressure of the tensiometer. These pressure variations are then reflected in the voltage signals captured by the measuring device. In the second stage, reading instabilities also emerged around 8:00 a.m. and approximately 3:30 p.m., but signal oscillations diminished, resulting in increased readings with fewer variations (Figure 4B). The fluctuations suggest that the system is gradually adjusting to variations in thermal conditions throughout the day. This may indicate improved thermal regulation of the tensiometer and sensor, resulting in more consistent and reliable readings over the daily measurement period. In the third phase, it was observed that signal variations between 6:00 a.m. and 9:30 a.m. did not exhibit the same pattern as in previous stages (Figure 4C). However, oscillations between 9:00 a.m. and 3:30 p.m. displayed a similar behavior to the second phase. Even when thermal conditions appear more stable during the morning, the gradually accumulated heat in the soil and sensor can still cause variations in the internal pressure of the tensiometer. These variations are then reflected in the voltage signals captured by the measuring device, demonstrating that thermal influence persists throughout the daily monitoring period (Liu & Dane, 1993; Romero et al., 2001).

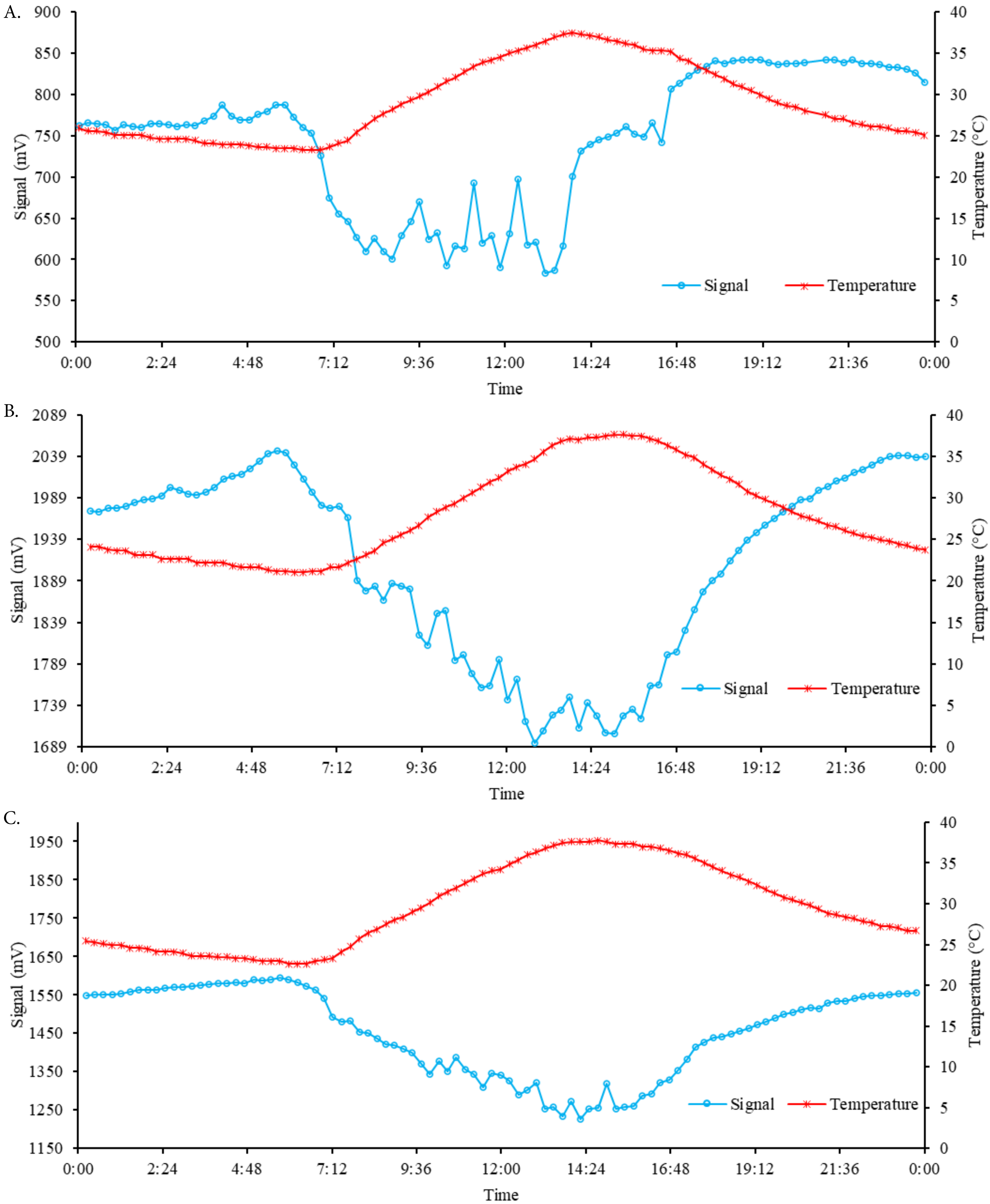
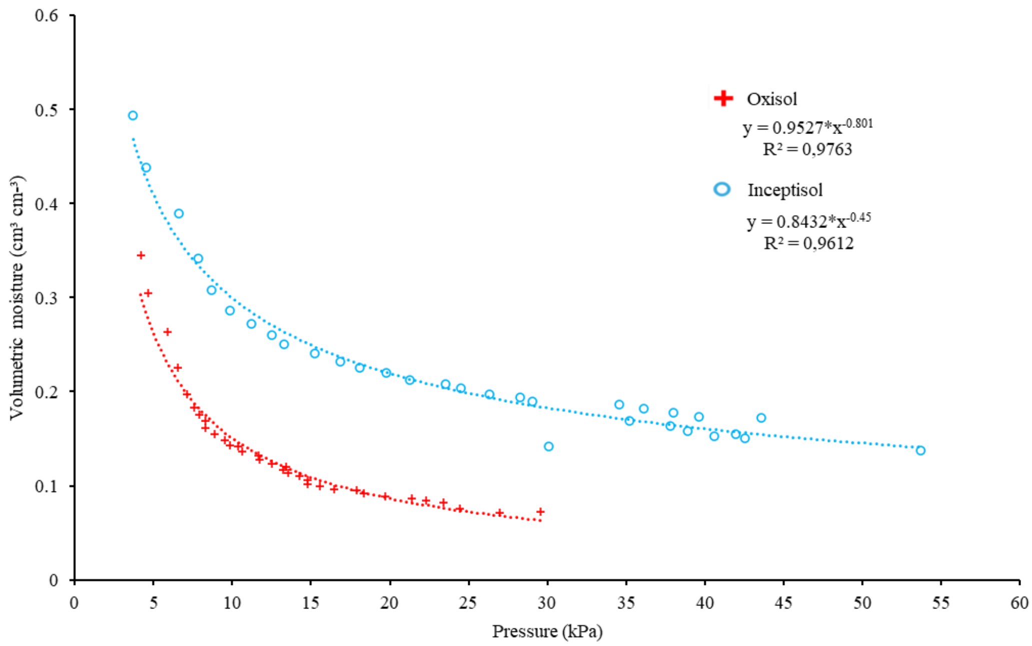


Figure 4. Influence of soil temperature on tensiometer readings performed at 15 (A), 30 (B), and 45 (C) days after the beginning of tests

These variations demonstrate the importance of considering temperature fluctuations when interpreting tensiometer data. It is recommended to take tensiometer readings during cooler times of the day, such as early morning, to ensure greater precision and consistency in measurements.

It is evident that there are variations in tensiometer readings depending on the time of the day, with noticeable fluctuations in the values. Instability issues are also reported in the readings between 10:00 a.m. and 6:00 p.m., suggesting that readings outside this time interval are advisable (Fujimaki & Yanagawa, 2019).

The relation between volumetric moisture data measured at 5:00 p.m. and signals from sensors at 6:00 a.m. indicated minimal influence of temperature on reading signals (Figure 5).



* - Significant at $p \leq 0.05$ by the F test; R^2 - Coefficient of determination

Figure 5. Calibration curves of the sensors based on the volumetric moisture for two types of soils with readings of volumetric moisture at 05:00 p.m. and sensor at 06:00 a.m.

There was a high coefficient of determination between volumetric moisture at 5:00 p.m. and the response of moisture sensors at 06:00 a.m. In both soils, the R^2 values were close to 1, indicating that the variation in sensor signals could accurately determine the variation in volumetric moisture in both soils. The results suggest that transducer readings can exhibit significant variations throughout the day, especially during the hottest hours. However, it is recommended that readings intended for irrigation management be taken during colder hours of the day, such as early in the morning, when there is minimal variation in readings (Pereira et al., 2020). Pramanik et al. (2022), who tested an irrigation system based on automated soil moisture sensors, obtained inferior results in which the calibration curve presented a R^2 value of 0.827. Verma & Pahuja (2021) comparing and recalibrating soil moisture sensors using regression and neural networks, found similar R^2 values of 0.9915.

Furthermore, sensor quality plays a crucial role in accurately determining soil moisture. High-quality sensors provide more reliable readings and are essential for the proper functioning and longevity of the soil moisture monitoring system.

Conclusions

1. The proposed soil moisture monitoring system can be a decision-making tool to accurately manage irrigation, resulting in intelligent and high-efficiency water use in Oxisols and Inceptisols.

2. Tensiometric measurements fluctuate with daily temperature variations in both soils and readings are recommended during the hours of the day with coldest temperatures to ensure the effective functioning of automation and irrigation control.

Author contributions: M.M.S. worked on performing the experiments and collecting data; M.M.S., O.N.S.N., P.A.G.F., and Y.C.S.S. worked on performing the data analysis and implementation of the computational models; N.S.D., S.N.D., and F.V.S.S. worked on the supervision, validation, and provision of material and instrumentation resources; M.A.M., A.R.A., and N.S.D. worked on review, editing the manuscript, and conducting a literature review.

Supplementary documents: There are no supplementary sources.

Conflict of interest: The authors declare no conflict of interest.

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