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CALIBRAÇÃO DE SENSOR PARA MONITORAMENTO DA UMIDADE DO SOLO

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1 RESUMO

Conhecer a umidade atual do solo de forma precisa é fundamental para um manejo eficiente de irrigação, visando a racionalização dos recursos hídricos fundamentado na sustentabilidade e na rentabilidade dos cultivos irrigados. Dessa forma, o objetivo deste trabalho foi calibrar o sensor modelo YL-69 e propor uma equação de calibração para o Argissolo Vermelho-Amarelo Distrófico na região do Cariri Cearense. O experimento foi conduzido em casa de vegetação na Universidade Federal do Cariri. O solo em questão foi locado em quatro vasos de 5 L, que teve a umidade monitorada diariamente da saturação até a secagem ao ar. A calibração foi avaliada por meio do emprego de índices estatísticos. A equação de calibração apresentou R^2 de 0,99 e erro quadrático médio (RMSE) de 0,03 $m^3\ m^{-3}$. Concluiu-se, que a calibração do sensor YL-69 apresenta precisão das leituras de umidade volumétrica do solo, porém, não sedo recomendado a sua utilização sem o emprego da equação de ajuste.

Palavras-chave: Teor de água no solo, sensor resistivo, acurácia.

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SENSOR CALIBRATION FOR MONITORING SOIL MOISTURE

2 ABSTRACT

Knowing the current soil moisture accurately is essential for efficient irrigation management, aiming to rationalize water resources on the basis of the sustainability and profitability of irrigated crops. Therefore, the objective of this work was to calibrate the model YL-69 sensor and propose a calibration equation for the Cariri Ceará region. The experiment was conducted in a greenhouse using a Dystrophic Red–Yellow Argisol, which was placed in four 5 L pots, with humidity monitored daily from saturation to air drying. Calibration was evaluated through

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the use of statistical indices. The calibration equation presented an R^2 of 0.99 and a root mean square error (RMSE) of 0.03 $m^3 m^{-3}$. It was concluded that the calibration of the YL-69 sensor presents accurate volumetric soil moisture readings; however, its use is not recommended without the use of an adjustment equation.

Keywords: Soil water content, capacitive sensor, accuracy.

3 INTRODUCTION

In the current scenario, the exponential growth of the population, the intensification of climate change events and the increase in pollution make the availability of fresh water increasingly scarce, generating great concern worldwide (Orouskhani *et al.,* 2023). These factors represent significant obstacles to agricultural development in several regions around the world (Songara; Patel, 2022).

In this context, the use of irrigation stands out as a fundamental strategy to increase the productivity of cultivated plants and the socioeconomic stability of cropping systems. (Alves *et al*., 2022). However, there is a need to ensure the rational use of water resources, aiming at increasing the quantity and quality of products, as well as the sustainability of irrigated areas (Menezes *et al.*, 2024b). To achieve these objectives, good irrigation management is essential, providing an increase in the productivity of water and other agricultural inputs or production factors, such as fertilizers and labor (Provenzano *et al*., 2020).

To better manage this water, estimating the actual soil moisture is essential and can be measured via direct and indirect methods. Direct methods involve separating water from the soil through chemical reactions and/or drying in an oven (Schwamback *et al*., 2023). Indirect methods, on the other hand, have several forms of execution, with emphasis on dielectric techniques and capacitance sensors, which stand out from other methods owing to the possibility of automation (Kulmány *et al*., 2022).

For automation purposes, Arduino stands out for being a low-cost platform capable of performing numerous operations. In addition, it has an intuitive development environment that is compatible with several operating systems (Cunha, 2022). However, the use of this platform associated with soil moisture monitoring sensors is still not widespread among farmers, and it is necessary to perform tests and calibrations of this equipment to obtain accurate and representative data. Thus, the objective of this work was to calibrate the YL-69 soil moisture sensor and propose a calibration equation for the Dystrophic Red--Yellow Argisol in the Cariri region of Ceará.

4 MATERIALS AND METHODS

The work was developed in a protected environment in the experimental area of the Center for Agricultural Sciences and Biodiversity (CCAB) of the Federal University of Cariri (UFCA), in Crato, CE (7°14'03” S and 39°24'34” W, altitude of 420 m), from June to July 2024. The climate of the region is classified as hot tropical, mild semiarid or hot subhumid tropical (Sousa, 2019). The soil used is classified as Abruptic Dystrophic Red--Yellow Argisol (Cearense Foundation for Meteorology and Water Resources, 2012), which is characteristic of the Cariri region of Ceará, whose physical characteristics are described in Table 1.

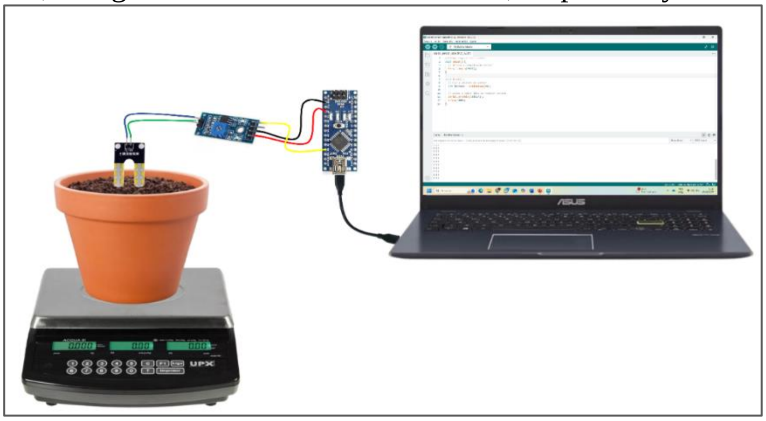
Table 1. Physical attributes of the studied soil

Depth	Particle Density	Soil Density	Total Porosity	Sand	Silt	Clay
--- m ---	--- kg dm $^{-3}$ ---	---- % ----	--- g kg $^{-1}$ ---			
0 – 0.40	2.86	1.41	50.53	857.72	18.58	123.69

Disturbed soil samples were collected at depths of 0 to 0.40 m. The collected soil was air-dried and sieved through 5 mm mesh for later allocation into 5 L pots, considering the soil density value obtained in the field. Four pots previously perforated at the base were used, initially filled with a layer of gravel (1 kg) and covered with Wipe fabric, with the remaining working volume of the buckets filled with 4.08 kg of moist soil (43.3% moisture at field capacity), which was calculated to maintain the original soil density.

The methodology was subsequently proposed by Jiménez *et al*. (2019), where the soil was saturated by capillarity, with buckets containing the soil placed inside a tank with water up to halfway, allowing the water to be translocated from the lowest part of the bucket to its surface. The pots were subsequently placed on a bench to drain excess water over a period of 24 hours, where it was assumed that the moisture level was equivalent to the field capacity. At this time, the first soil weights were obtained via a scale with an accuracy of ± 0.2 g, and the soil moisture readings were determined via the YL-69 resistive sensor. The choice of sensor was based on a low-cost model that has been most cited in soil moisture monitoring studies.

Figure 1. Operational scheme used to perform gravimetric and volumetric readings of soil moisture, using a scale and the Arduino nano, respectively.



Source: Authors (2025)

The weights and soil moisture readings of the pots were obtained daily at 8:00 a.m. The soil moisture data recorded by the resistive sensor were sent to an Arduino board, which was punctually displayed on the Arduino serial monitor via a computer and then transferred to an Excel spreadsheet (Figure 1). The data were recorded daily until the mass of the set (pot, gravel, wipe fabric and soil) remained constant for at least three consecutive readings.

The daily weight of the set was used to calculate the gravimetric soil water content via the standard method, according to equation (1). The soil water content was determined as a function of the gravimetric moisture content and was used as a basis for sensor calibration. A water density of 1.0 Mg m $^{-3}$ and a soil density, according to equation

(2), were also considered. These procedures were carried out as suggested by Jiménez *et al.* (2019).

$$U = \frac{Ma}{Mss} \quad (1)$$

$$\theta = U \times Ds \quad (2)$$

Where U is the gravimetric soil water content, gg $^{-1}$; θ is the volumetric moisture, m ^{3} m $^{-3}$; Ma is the mass of water in the soil, g; Mss is the dry mass of the soil, g; and Ds is the soil density, g cm $^{-3}$.

The measured volumetric water content, Y (m ^{3} m $^{-3}$), was related to the sensor readings, X (m ^{3} m $^{-3}$), via regression analysis. This relationship allows us to have a calibration model, which would result in estimated volumetric moisture values from sensor readings. With the estimated and observed values, the models are evaluated (P >> X - estimated moisture; O >> Y - observed moisture). The soil moisture estimation models were evaluated on the basis of statistical indices such as the coefficient of determination (R^2), the root mean square error (RMSE) via equation (3), Willmott's (1981) concordance index expressed via equation (4) and Pearson's correlation coefficient (r) via equation (5).

$$RMSE = \left[\frac{1}{n} \sum_{i=1}^{n}(O_i - P_i)^2\right]^{0,5} \quad (3)$$

$$d = 1 - \left[\frac{\sum_{i=1}^{n}(Pi - Oi)^2}{\sum_{i=1}^{n}(|Pi - \bar{O}| + |Oi - \bar{O}|)^2}\right] \quad (4)$$

$$r = \frac{\sum_{i=1}^{n}(Oi - \bar{O})\,(Pi - \bar{P})}{[\sum_{i=1}^{n}(Oi - \bar{O})^2]^{0,5}\ [(Pi - \bar{P})^2]^{0,5}} \quad (5)$$

where n is the number of observations, Hi is the value measured via the standard method, and Pi is the value estimated by the sensors (i = 1, 2 …. n), and $\bar{O}$ is the average of the measured values.

The Willmott index ranges from 0 to 1; a value closer to 1 indicates perfect agreement between the measured (standard) and estimated values, whereas 0 indicates no agreement between the values (Walker; Willgoose; Kalma, 2004; Menezes *et al.*, 2024a). The confidence index (c) proposed by Camargo and Sentelhas (1997) was also calculated according to equation (6).

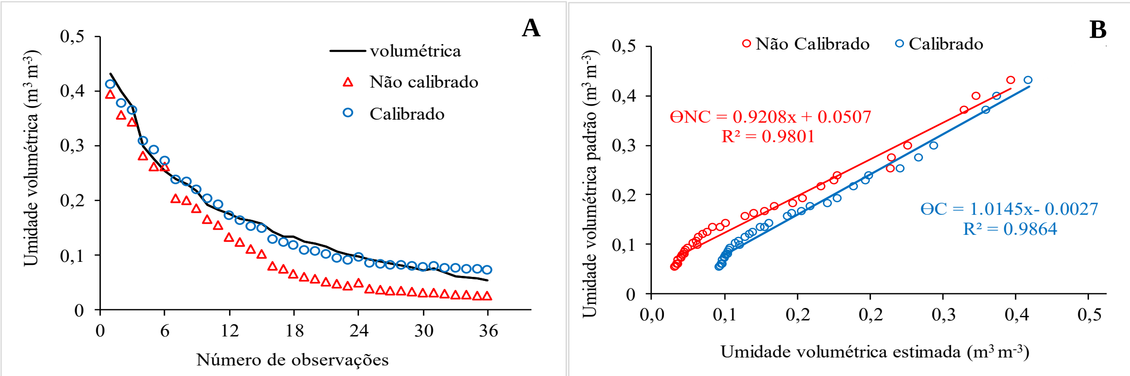
$$c = d \times r \quad (6)$$

The sentiment agreement index (c) can be interpreted as follows: ≤ 0.40 very bad, from 0.41 to 0.50 bad, from 0.51 to 0.60 poor, 0.61 to 0.65 average, from 0.66 to 0.75 good, from 0.76 to 0.85 very good and >0.85 excellent (Camargo; Sentelhas, 1997).

5 RESULTS AND DISCUSSION

The variation in the soil water content over the evaluated period is shown in Figure 2A. The drying curve for the studied soil was determined, where the volumetric soil moisture content (y-axis) was related to the number of observations recorded in the study (x-axis). Thirty-six days of observations were necessary, with one observation per day, for the soil to reach mass and moisture stability.

Figure 2. Drying curve for an abrupt Dystrophic Red–Yellow Argisol (A). Standard volumetric moisture and its correlation with the moisture estimated by the YL-69 sensor with and without calibration (B). ΔNC = volumetric moisture of the uncalibrated sensor**,** and ΔC = volumetric moisture of the calibrated sensor.



Source: Authors (2025)

Before calibration, the sensor readings ranged from 0.39 to 0.03 m ^{3} m $^{-3}$, tending to underestimate the standard curve, which ranged from 0.43 to 0.05 m ^{3} m $^{-3}$. The sensor readings were more accurate in the first 7 days of recordings; after this period, a loss in the sensitivity of the readings was observed, leading to records lower than the standard. However, calibration improved the accuracy of the sensor, which began to record a variation of 0.41 to 0.07 m ^{3} m $^{-3}$ after calibration. Similar results were also reported by Jiménez *et al*. (2019), calibrating capacitive sensors for soils characteristic of the Brazilian Northeast.

The calibration equation for the YL-69 sensor was obtained through the correlation between the average gravimetric moisture content of the buckets, which was based on the soil density, and the average volumetric moisture content estimated by the sensor (Figure 2B). An R2 of 0.99 was obtained for the adjustment equation, a result superior to those found by Jiménez *et al.* (2019), Pizetta *et al.* (2017), whose R^2 values were 0.96 and 0.72 for the calibration equations of a Yellow Latosol and a Dystrophic Red Argisol, respectively.

After calibration, the volumetric moisture values estimated by the sensor improved significantly, approaching the 1:1 line, which represents values closer to the real values. However, there was still a tendency to underestimate the real values in readings below 0.1 m ^{3} m $^{-3}$ and in the range of 0.2--0.35 m ^{3} m $^{-3}$. The calibration process of the YL-69 sensor improved the accuracy of the soil moisture readings (Table 2), with a reflection, mainly, in the index associated with the error (RMSE).

Table 2. Statistical indices for the YL-69 sensor before and after calibration for both soils.

Sensor	**Indices**				**Error (m ^{3} m- ^{3})**
	d	***r***	***c***	**Performance**	**RMSE**
Not calibrated	0.971	0.960	0.932	Excellent	0.031
Calibrated	0.980	0.967	0.947	Excellent	0.026

The deor index moved even closer to unity, representing an improvement in the performance and accuracy of the readings and helping *c* to remain excellent.

6 CONCLUSIONS

Calibration of the YL-69 sensor improved the accuracy of soil volumetric moisture readings for a Dystrophic Red–Yellow Argisol. Although the performance remained excellent for both the calibrated and uncalibrated sensors, there was an improvement in the accuracy of the sensor readings after calibration, improving values such as the root mean square error and agreement indices. Therefore, its use in abrupt dystrophic Red--Yellow Argisol soils should be preceded by a calibration process in which the adjustment equation is used to obtain more accurate soil moisture values.

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