ISSN 1808-8546 (ONLINE) 1808-3765 (CD-ROM)

CALIBRAÇÃO DE SENSORES PARA ESTIMATIVA DE UMIDADE EM QUATRO CLASSES DE SOLO

IGOR ALEXANDRE DE SOUZA[1]; HENRIQUE LOPES COIMBRA[1]; WESLEY ESDRAS SANTIAGO[1], RAFAEL FARIA CALDEIRA[1]; DANIEL MAI[1] E DANIEL CAMPANELLI DE ANDRADE[1]

[1]Instituto de Ciências Agrárias – ICA, Universidade Federal dos Vales do Jequitinhonha e Mucuri – UFVJM, Avenida Universitária, 1000, Universitários, 38610-036, Unaí, MG Brasil
igor.alexandre@ufvjm.edu.br; henrique.lopes@ufvjm.edu.br; wesley.santiago@ufvjm.edu.br; rafael.faria@ufvjm.edu.br; daniel.mai@ufvjm.edu.br; daniel.campanelli@icrop.com.br

1 RESUMO

Os sensores de umidade do solo são uma ferramenta útil para otimizar o uso da água, mas devem ser calibrados localmente para garantir precisão. Isso envolve considerar a sensibilidade desses sensores aos atributos naturais do solo, que variam de acordo com sua classe e particularidades. O objetivo desse estudo foi avaliar e calibrar três sensores de umidade do solo (HidroFarm, Vergtrug Care e PMS710) em quatro diferentes classes de solo: Latossolo Vermelho Distrófico, Latossolo Amarelo Distrófico, Nitossolo Vermelho Distrófico e Cambissolo Háplico. Foram utilizadas 12 amostras de solo indeformadas coletadas em colunas de PVC de 112 mm de diâmetro por 200 mm de altura. As amostras foram saturadas com água destilada, e os sensores foram inseridos imediatamente após a saturação. Em razão das características específicas de cada sensor e tipo de solo, foram desenvolvidas curvas de calibração personalizadas. A avaliação das curvas de calibração, considerando o coeficiente de determinação Kendall e Pearson e os valores de *p*, revelou que os sensores Vergtrug Care e PMS710 demonstraram resultados estatisticamente significativos e são, portanto, recomendados para a estimativa de umidade volumétrica nos solos estudados.

Keywords: curvas de calibração, eficiência de sensores, propriedades físicas do solo, umidade volumétrica.

SOUZA, I. A. de; COIMBRA, H. L.; SANTIAGO, W. E., CALDEIRA, R. F.; MAI, D. e ANDRADE, D. C. de
SENSOR CALIBRATION FOR MOISTURE ESTIMATION IN FOUR SOIL CLASSES

2 ABSTRACT

Soil moisture sensors are useful tools for optimizing water use but need to be calibrated locally to ensure accuracy. This involves considering the sensitivity of these sensors to natural soil attributes, which vary according to their class and characteristics. The aim of this study was to evaluate and calibrate three soil moisture sensors (HidroFarm, Vergtrug Care and PMS710) in four different soil classes: dystrophic Red Latosol, dystrophic Yellow Latosol, dystrophic Red Nitosol and a Haplic Cambisol. Twelve undisturbed soil samples were collected from PVC

Recebido em 15/02/2023 e aprovado para publicação em 09/10/2023
DOI: http://dx.doi.org/10.15809/irriga.2023v28n4p720-730

columns with a diameter of 112 mm and a height of 200 mm. The samples were saturated with distilled water, and the sensors were inserted immediately after saturation. Owing to the specific characteristics of each sensor and soil type, customized calibration curves were developed. The evaluation of these curves, which is based on the criteria of the coefficient of determination, Kendall's coefficient, Pearson's coefficient, p value and mean squared error, demonstrated that only the Vergtrug Care and PMS710 sensors are recommended for estimation of volumetric moisture in the studied soils.

Keywords: calibration curves, moisture content, sensor efficiency, soil properties.

3 INTRODUCTION

Soil moisture plays a crucial role in almost all terrestrial processes, with significant impacts on the hydrological cycle and human activities (Ro Timi Ojo; Bullock; Fitzmaurice,2015). Maintaining adequate moisture levels is essential for crop productivity and healthy plant development (Krueger; Ochsner; Quiring, 2019). Monitoring soil moisture provides vital information on water availability, soil health, and soil water retention capacity, which are key indicators of the sustainability of agricultural systems (Kashyap; Kumar, 2021).

Several soil moisture monitoring devices, which measure temporal variability at short intervals, are used in precision agriculture, landscape monitoring, and long-term global mapping. Although traditional methods, such as gravimetric and tensiometric methods, are widely recognized (Majhi; Sarkar, 2019; Singh *et al*., 2019; Sharma *et al*., 2018), the challenges associated with sample collection and processing and technological advancements have driven the development of modern electronic sensors. These sensors offer the ability to remotely measure, record, and transmit soil moisture instantly (Cássaro *et al*., 2019; Santos Neto *et al*., 2020).

Although accurate, electronic soil moisture sensors require field calibration to ensure that measured values accurately reflect actual moisture (Sena *et al*., 2020). The heterogeneous distribution of soil types in agricultural areas (Santos Neto *et al*., 2020) requires the development of specific calibration curves for each soil type, ensuring the proper use of sensors.

The calibration of sensors in different soil classes is crucial since the physical and chemical characteristics of the soils directly influence the accuracy of the measurements. Soils such as Ultisols, Latosols and Nitosols, which have distinct textures and compositions, present varied behaviors in relation to water retention, making specific calibrations essential (Pizetta *et al*., 2017). Sandy soils, such as Neossolos Quartzarenic and Cambisols, may require different adjustments to ensure sensor accuracy (Miranda *et al*., 2007). Calibration allows efficient monitoring of moisture and optimizes water management, which is essential for agricultural sustainability.

The differences between temperate and tropical soils, such as Oxisols and Nitosols, directly influence moisture measurement, making pedotransfer functions developed for temperate soils inadequate for tropical soils. The microaggregate structure of tropical soils, with iron and aluminum oxides, affects water retention and sensor response. Therefore, specific calibrations for each soil class are essential for obtaining more reliable moisture measurements (Tomasella; Hodnett, 2004).

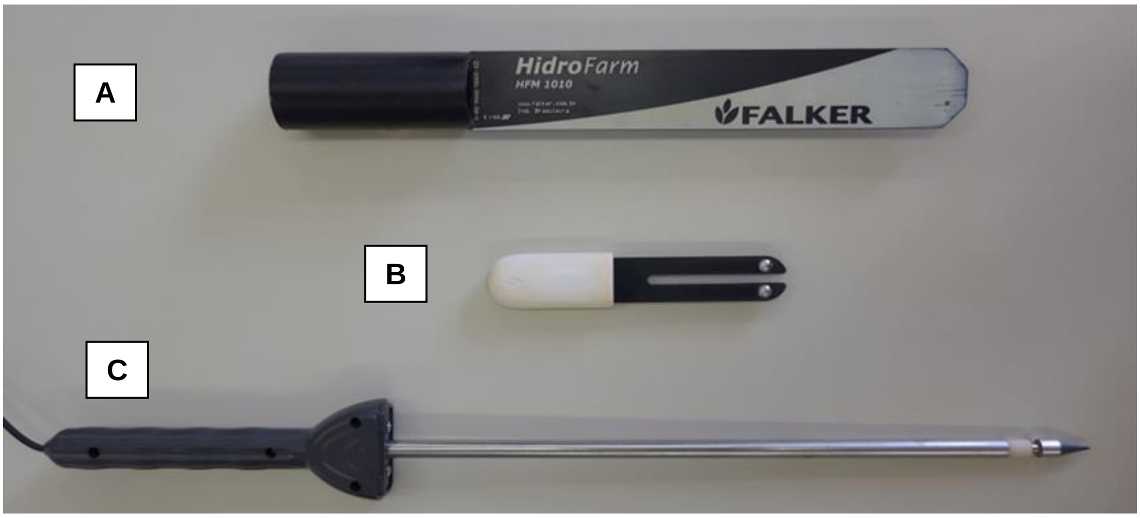
The hypothesis of this study is that the accuracy of electronic soil moisture sensors varies according to the intrinsic characteristics of different soil classes. The objective is to evaluate and calibrate the sensors via gravimetric methodology, adjust the measurements to adequately reflect the characteristics of different soils and optimize the accuracy of moisture measurements.

4 MATERIALS AND METHODS

4.1. Location and experimental context

The experiment was conducted at the Research Laboratory of the Institute of Agricultural Sciences of the Federal University of the Jequitinhonha and Mucuri Valleys (ICA/UFVJM), located in Unaí, MG. The HidroFarm, Vergtrug and Care and PMS710 (Figure 1) and four soil classes were classified according to Santos *et al*. (2018) as: Typical Dystrophic Red Latosol with moderate A horizon, very clayey texture, kaolinitic (LVd1); Plinthosol Dystrophic Yellow Latosol, moderate A horizon, very clayey kaolinitic texture (LAd); Typical Dystrophic Red Nitosol, prominent A horizon, clayey texture, kaolinitic (NVd); and Cambisol Haplic Tb Typical eutrophic, moderate A horizon, clayey texture, kaolinitic (CXbe2). The soils in the study area have as their parent material predominantly siltstones and claystones of the Paraopeba Formation, in addition to quartz-sandstones, phyllites and siltstones of the Paranoá Formation, both of which are members of the Bambuí Group.

Figure 1. Soil moisture sensors used. (a) HidroFarm sensor; (b) Vergtrug sensor; (c) PMS710 sensor.



Source: Authors (2023)

Soil samples were collected at the Santa Paula Experimental Farm (FESP), which belongs to the Institute of Agricultural Sciences of the Federal University of the Jequitinhonha and Mucuri Valleys (ICA/UFVJM) and is located in the municipality of Unaí-MG, with latitude S 16°26'11.5" and longitude W46°53'55.4"W, at an average altitude of 622 m and flat relief. The region is part of the cerrado biome, and the local climate, according to the Köppen classification, is type Aw - tropical with a dry winter season. The average annual temperature is 23.5 °C, and the average rainfall is 1275 mm.

4.2. Sampling description and methodology

The soil classes in the toposequence are Dystrophic Red Latosol (LVd1), which predominates at the top; Dystrophic Yellow Latosol (LAd), which occupies the shoulder position; Dystrophic Red Nitosol (NVd), which occurs in the midslope/foothill; and Cambisol Haplic eutrophic (CXbe2), which is located at the foot, with an extension of 844 m and an elevation variation of 19 m.

The granulometric analysis was performed by the pipette method, using 0.1 N NaOH solution as a dispersing agent, according to the recommendations of EMBRAPA (2017). The soil density and particle density were determined following the methods described in the Soil Analysis Methods Manual (EMBRAPA, 2017). All analyses were conducted at the Soil Laboratory of ICA/UFVJM, Unaí Campus, as shown in Table 1.

Table 1. Average values of soil density (g cm $^{-3}$), particle density (g cm $^{-3}$), total pore volume (%) and granulometry for the different soil classes.

Variable	**LVd1**	**LAd**	**NVd**	**CXbe2**
	Depths from 0 - 20			
Ds (g cm $^{-3}$)	1.26	1.20	1.22	1.32
DP (g cm $^{-3}$)	2.60	2.61	2.72	2.59
VTP (%)	48.46	45.97	44.85	50.96
Clay (%)	66	69	46	43
Silt (%)	22	23	35	36
Sand (%)	12	8	19	21

LVd1: Typical Dystrophic Red Latosol with moderate A horizon, very clayey texture, kaolinitic; LAd: Plinthosol Dystrophic Yellow Latosol, moderate A horizon, very clayey kaolinitic texture; NVd: Typical Dystrophic Red Nitosol, prominent A horizon, clayey texture, kaolinitic; CXbe2: Cambisol Haplic Tb. Typical eutrophic, moderate A horizon, clayey texture, kaolinitic.
Source: Authors (2023)

Three undisturbed samples were collected per soil class, using PVC cylinders that were 200 mm in height and 112 mm in internal diameter, representing the 0–200 mm depth layer. The three samples were considered experimental replicates for each soil class. After collection, the samples were properly packaged for transport and sent to the ICA/UFVJM Research Laboratory. In the laboratory, to ensure that the mass of soil material was contained only inside the cylinders, the excess material was removed. After preparation, the samples were individually subjected to slow saturation by capillarity with distilled water.

4.3 Experimental procedures and statistical analysis

After saturation, the samples were weighed, and the sensors were inserted and immersed throughout the evaluation period. The bottoms of the samples were supported on a sand column to ensure homogeneous drying. The samples corresponding to the three replicates of each soil class were kept in a laboratory environment with a controlled temperature of 25 °C. Moisture readings were taken daily for 7 days, always at the same time, three times of day at 8 am, 12 pm and 6 pm. Simultaneously, with the acquisition of moisture data from the instruments, the soil columns were weighed to determine the gravimetric moisture, as shown in Figure 2.

Figure 2. Undeformed sample during the weighing process after sensor readings.

Source: Authors (2023)

Gravimetric moisture was obtained according to the equation

$\mu = 100 \times (Mu - Ms/Ms)$ (1)

where μ is the moisture content based on mass, %; Mu is the mass of water, grams; Ms is the mass of dry soil, grams; and 100 is the conversion factor to a percentage.

The soil density (Ds) was calculated at the end of the evaluations by dividing the dry soil mass by the total volume of soil in the volumetric cylinder after drying the samples in an oven at 105 °C for 24 hours. Thus, using gravimetric moisture, it was possible to calculate volumetric moisture through the following equation: $\theta = \mu * \mathrm{D}\, s$. The correlation curves between the sensor readings and the actual volumetric humidities determined by the area–mass–volume ratio were fitted with statistical analysis performed in the MATLAB program (MathWorks, MA, USA) version R2015.

5 RESULTS AND DISCUSSION

The results that allowed the calibration of the sensors for the different soil types are presented below. Table 2 details the physical–hydraulic characteristics of the calibration columns for the soil types LVd1, LAd, NVd and CXbe2.

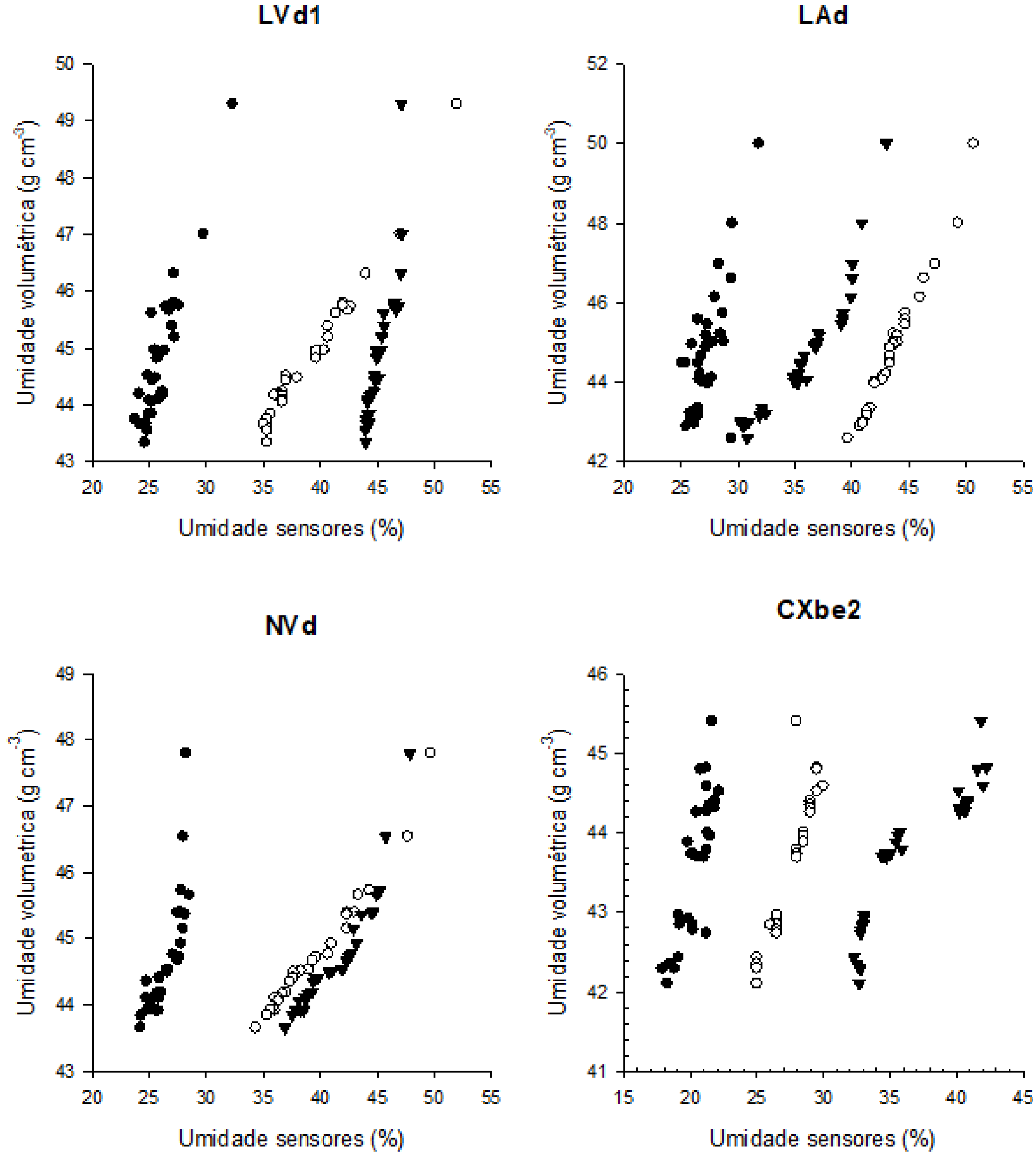
Table 2. Average values of soil density (g cm $^{-3}$), gravimetric moisture (gg $^{-1}$) and volumetric moisture (g cm $^{-3}$) of the soil columns used for calibration in different soil classes.

Soil	**Density (g cm $^{-3}$)**	**Gravimetric humidity (gg $^{-1}$)**	**Volumetric humidity (g cm $^{-3}$)**
LVd1	1.26	39.2	49.4
LAd	1.20	41.7	50.0
NVd	1.22	39.3	47.9
CXbe2	1.32	34.4	45.4

LVd1 = Typical Dystrophic Red Latosol with moderate A horizon, very clayey texture, kaolinitic; LAd = Plinthosol Dystrophic Yellow Latosol, moderate A horizon, very clayey kaolinitic texture; NVd = Typical Dystrophic Red Nitosol, prominent A horizon, clayey texture, kaolinitic; CXbe2 = Cambisol Haplic Tb Typical eutrophic, moderate A horizon, clayey texture, kaolinitic.
Source: Authors (2023)

The volumetric water content measured by HidroFarm, Vergtrug sensors Care and PMS710 for soils of classes LVd1, LAd, NVd and CXbe2 is presented in Figure 3, allowing a direct comparison with the measured volumetric moisture values.

Figure 3. Volumetric water content measured by different sensors. (a) LVD1; (b) LAd; (c) NVd; and (d) CXbe2.



Source: Authors (2023)

The analysis of different sensors for the same soil type reveals low agreement between the sensors, indicating that the use of a single model to ensure greater accuracy is recommended. According to Nagahage, Nagahage and Fujino (2019), the performance of soil moisture sensors depends directly on the characteristics of the soil analyzed. This perspective helps explain the variability of the sensors for each soil type analyzed in this work, especially those identified in LVd1 and LAd.

The study by Gava, Silva and Baio (2016) revealed that capacitive sensors underestimate the real moisture content by approximately 8% in clayey soils, especially in measurements close to field capacity. In sandy soils, owing to faster drainage, the actual moisture content underestimated by the capacitive sensor is approximately 4%.

The results showed that the Vergtrug sensors Care and PMS710 exhibited satisfactory performance in estimating volumetric moisture, especially in soils such as Red and Yellow Latosols, Red Nitosol and the Cambisol Haplico, as long as they are properly calibrated for each soil class, as shown in Table 3. This adjusted calibration is essential, considering that textural variations between soils, such as clay, silt, and sand contents, according to Table 1, directly affect water retention and movement in the soil, influencing sensor readings. In contrast, the HidroFarm sensor demonstrated inferior performance, suggesting a lower capacity to adapt to soils with large textural variations, which highlights the importance of accurate calibration to ensure measurement reliability, as shown in Table 3. Studies indicate that specific calibrations are essential to compensate for textural variations, ensuring reliable readings, especially in clayey or sandy soils, where the water retention capacity significantly differs (Feng; Sui, 2020; Lim; Herrera; Cruz, 2024).

Previous studies highlighted the importance of the specific calibration of sensors, considering the physical and chemical properties of each soil type, such as texture and water retention capacity, which directly influence the accuracy of measurements (Babangida *et al*., 2014; Zanetti *et al*., 2015). This adjustment is critical not only for ensuring consistent measurements but also for optimizing the performance of moisture monitoring technologies in diverse agricultural contexts (Kashyap, Kumar, 2021; Hodges; Tagert; Paz, 2022).

Table 3. Performance measurements of the static calibration of moisture sensors in different soils must have a font size of 12, width of 10 or 15 cm, and first line in bold; if necessary, the data must be divided into two tables or inverted rows with columns.

Sensor	**Type of soil**	**Calibration curve**	**R^2**	**RMSE**	**P value**	**Pearson**	**Kendall**
HydroFarm	LVd1	$y = 0.015x^2 - 0.14x + 39$	0.85	0.492	0.08	0.32	0.59
Vergtrug Care	LVd1	$y = -0.0021x^3 + 0.28x^2 - 12.04x + 210.4$	0.92	0.36	0.00	0.90	0.82
PMS710	LVd1	$y = 0.07x2 - 5.3x + 143$	0.81	0.55	0.00	0.90	0.89
HydroFarm	LAd	$y = 0.1039x^2 - 5.29x + 104.4$	0.57	1.05	0.00	0.72	0.48
Vergtrug Care	LAd	$y = 0.6538x + 16.3$	0.98	0.22	0.00	0.99	0.96
PMS710	LAd	$y = 0.004329x^3 - 0.435x^2 + 14.84x - 127.9$	0.97	0.29	0.30	0.18	0.86
HydroFarm	NVd	$y = 0.06012x^3 - 4.567x^2 + 115.8x -$	0.72	0.52	0.00	0.79	0.80
Vergtrug Care	NVd	$y = 0.001135x^3 - 0.1352x^2 + 5.551x - 33.54$	0.99	0.09	0.00	0.98	0.97
PMS710	NVd	$y = 0.004837x^3 - 0.5825x^2 + 23.55x - 275.2$	0.98	0.14	0.00	0.94	0.97
HydroFarm	CXbe2	$y = -0.01003x^2 + 1.039x + 26.61$	0.68	0.53	0.00	0.82	0.62
Vergtrug Care	CXbe2	$y = -0.001492x^2 + 0.6069x + 28$	0.87	0.34	0.00	0.93	0.85
PMS710	CXbe2	$y = 0.009451x^3 - 1.078x^2 + 41x - 476.3$	0.95	0.22	0.00	0.92	0.88

LVd1 = Typical Dystrophic Red Latosol with moderate A horizon, very clayey texture, kaolinitic; LAd = Plinthosol Dystrophic Yellow Latosol, moderate A horizon, very clayey kaolinitic texture; NVd = Typical Dystrophic Red Nitosol, prominent A horizon, clayey texture, kaolinitic; CXbe2 = Cambisol Haplic Tb Typical eutrophic, moderate A horizon, clayey texture, kaolinitic.
Source: Authors (2023)

Sena *et al.* (2020) highlighted that the calibration of soil moisture sensors must be customized for both the soil type and its different layers since management can alter the soil density, leading to inaccurate readings, even with calibration curves specific to the soil type under study.

The HidroFarm and PMS710 sensors did not yield statistically significant results, with P = 0.08 for LVd1 and P = 0.30 for the LAd soil, values higher than the adopted significance level ($P < 0.05$). However, the Kendall correlation coefficient revealed that all the treatments involving sensors and soils presented correlations significantly different from zero, with an emphasis on the HidroFarm sensor, which presented the lowest correlation values in all the soils analyzed.

The calibration curves for the sensors presented determination coefficients ranging from 0.57 to 0.99. The determination coefficient (R^2) indicates the proportion of data variability explained by the model, with values close to 1.0 indicating a better fit of the model, which reflects greater precision and accuracy of the sensors.

6 CONCLUSION

The use of soil moisture sensors to estimate the water content in agricultural soils has demonstrated significant benefits in terms of measurement accuracy. The performance of the calibration curves revealed that, with the exception of the HidroFarm sensor, the Vergtrug sensors Care and PMS710 were effective for estimating volumetric moisture in Dystrophic Red Latosol, Dystrophic Yellow Latosol, Dystrophic Red Nitosol and Cambisol Haplico as long as they were calibrated according to the specific characteristics of each type of soil. Precise calibrations were essential to ensure accurate measurements of soil moisture, highlighting the need for adjustments according to the specific conditions of each soil.

7 REFERENCES

BABANGIDA, NM; ASKARI, M.; YUSOF, K. W.; MUHAMMAD, RU M. Comparison of soil water retention functions for humid tropical soils. **Applied Mechanics and Materials** , Zürich, v. 567, p. 8-13, 2014.

CÁSSARO, FAM; OLIVEIRA, JAT; CRUZ, H.; PIRES, LF Use of a humidity sensor for Arduino in determining the characteristic curve of water retention by a porous system. **Brazilian Journal of Physics Teaching** . São Paulo, v. 42, p. e20190130, 2019.

EMBRAPA. **Manual of soil analysis methods** . 3rd ed. Rio de Janeiro: Embrapa Soils, 2017.

FENG, G.; SUI, R. Evaluation and calibration of soil moisture sensors in undisturbed soils. **Transactions of the ASABE** , Michigan, v. 63, no. 2, p. 265-274, 2020.

GAVA, R.; SILVA, EE; BAIO, FHR Calibration of electronic moisture sensor in different soil textures. **Brazilian Journal of Biosystems Engineering** , Tupã , v. 10, no. 2, p. 154-162, 2016.

HODGES, B.; TAGERT, ML; PAZ, JO Use of a crop model and soil moisture sensors for estimating soil moisture and irrigation applications in a production soybean field. **Irrigation Science** , New York, vol. 40, n. 6, p. 925-939, 2022.

KASHYAP, B.; KUMAR, R. Sensing methodologies in agriculture for soil moisture and nutrient monitoring. **IEEE Access** , Piscataway,v. 9, p. 14095-14121, 2021.

KRUEGER, ES; OCHSNER, TE; QUIRING, SM Development and evaluation of soil moisture-based indices for agricultural drought monitoring. **Agronomy Journal** , Basel, v. 111, no. 3, p. 1392-1406, 2019.

LIM, G. R.; HERRERA, S. X. O.; CRUZ, F. R. G. Selection of Suitable Soil Moisture Sensor for Clay Soil. *In*: IEEE INTERNATIONAL CONFERENCE ON AUTOMATIC CONTROL AND INTELLIGENT SYSTEMS (I2CACIS), Shah Alam, 2024. **Proceedings** […]. Shah Alam: IEEE, 2024. p. 308-313.

MAJHI, T.; SARKAR, N. Study on soil moisture variations in responding to Tensiometer and soil moisture meter with respect to gravimetric method **.** **International Journal of Chemical**

Studies , New Delhi, vol. 7, no. 4, p. 3179-3188, 2019.

MIRANDA, FR; SANTANA, MGS; SOUZA, CCM; OLIVEIRA, CHC Calibration of the ECH2O dielectric sensor in two types of soil. **Magazine Science Agronomics** , Fortaleza, v. 38, n. 3, p. 317-321, 2007.

NAGAHAGE, EAAD; NAGAHAGE, ISP; FUJINO, T. Calibration and validation of a low-cost capacitive moisture sensor to integrate the automated soil moisture monitoring system. **agriculture** , Basel, v. 9 n. 7, p. 141-151, 2019.

PIZETTA, SC; RODRIGUES, RR; PEREIRA, GM; PACHECO, FED; VIOLA, MR; LIMA, LA Calibration of a capacitive sensor for estimating moisture in three soil classes. **Irriga** , Botucatu , v. 22, n. 3, p. 458-468, 2017.

RO TIMI OJO, E.; BULLOCK, PR; FITZMAURICE, J. Field performance of five soil moisture instruments in heavy clay soils. **Soil Science Society of America Journal** , Madison, vol. 79, no. 1, p. 20-29, 2015.

SANTOS NETO, SM; ANTONINO, ACD; COUTINHO, AP; BARROS, CAA; SOARES, WA Performance and calibration of a TDR sensor in soils of the state of Pernambuco, Brazil. **Aidis Journal of Engineering and Sciences Environmental** : Research , development and practice , Coyoacán, v. 13, no. 1, p. 33-476, 2020.

SANTOS, HG; JACOMINE, PKT; ANJOS, LD; OLIVEIRA, V. Á.; LUMBRERAS, JF; COELHO, MR; OLIVEIRA, JB **Brazilian soil classification system** . Brasília, DF: Embrapa, 2018.

SENA, CCRS; ALVES JUNIOR, J.; DOMINGOS, MVH; ANTUNES JUNIOR, EJ; BATTISTI, R.; EVANGELISTA, AWP; CASAROLI, D. Calibration of the EC-5 capacitive soil moisture sensor in response to soil particle size. **Brazilian Journal of Development** , São José dos Pinhais , v. 6 n. 4, p. 17228-17240, 2020.

SHARMA, P.K.; KUMAR, D.; SRIVASTAVA, HS; PATEL, P. Assessment of different methods for soil moisture estimation: A review. **Journal of Remote Sensing & GIS** , Noida, v. 9, n. 1, p. 57-73, 2018.

SINGH, AK; BHARDWAJ, AK; VERMA, CL; MISHRA, VK; SINGH, AK; ARORA, S.; SHARMA, N.; OJHA, RP Soil Moisture Sensing Techniques for Scheduling Irrigation. **Journal of Soil Salinity and Water Quality** , New Delhi, v. 11 n. 1, p. 68-76, 2019.

TOMASELLA, J.; HODNETT, M. Pedotransfer functions for tropical soils. **Developments in Soil Science** , Aberdeen, v. 30, p. 415-429, 2004.

ZANETTI, SS; CECÍLIO, RA; SILVA, VH; ALVES, EG General calibration of TDR to assess the moisture of tropical soils via artificial neural networks. **Journal of Hydrology**, Sacramento, vol. 530, p. 657-666, 2015.