

## DESENVOLVIMENTO E CALIBRAÇÃO DE UM SENSOR DE UMIDADE DO SOLO DE BAIXO CUSTO COM ESP32 PARA APLICAÇÃO EM LATOSSOLOS VERMELHOS

**THIAGO HENRIQUE DE OLIVEIRA<sup>1</sup>; MATHEUS HENRIQUE ANDRADE DE PAULA<sup>2</sup>; NATALIA LOURENÇO DA SILVA<sup>3</sup>; GABRIEL BARBOSA DO PRADO<sup>4</sup>; SÉMEBBER SILVA LINO<sup>5</sup>**

<sup>1</sup> Prof. Doutor, Departamento de Agronomia, Universidade Estadual de Goiás, Avenida Brasil N° 435, CEP:75860-000, Quirinópolis, Go; Brasil, [thiago.henrique@ueg.br](mailto:thiago.henrique@ueg.br); ORCID (<https://orcid.org/0000-0003-4240-7952>).

<sup>2</sup> Graduando em Agronomia, Departamento de Agronomia, UEG. Avenida Brasil N° 435, CEP:75860-000, Quirinópolis, Go; Brasil, [matheushenriqu20e776@gmail.com](mailto:matheushenriqu20e776@gmail.com); ORCID (<https://orcid.org/0009-0004-0463-0525>).

<sup>3</sup> Graduando em Agronomia, Departamento de Agronomia, UEG. Avenida Brasil N° 435, CEP:75860-000, Quirinópolis, Go; Brasil, [natalialou79@gmail.com](mailto:natalialou79@gmail.com); ORCID (<https://orcid.org/0009-0007-0757-9878>).

<sup>4</sup> Graduando em Agronomia, Departamento de Agronomia, UEG. Avenida Brasil N° 435, CEP:75860-000, Quirinópolis, Go; Brasil, [gabrielbarbosadoprado505@gmail.com](mailto:gabrielbarbosadoprado505@gmail.com); ORCID (<https://orcid.org/0009-0006-7917-4370>).

<sup>5</sup> Prof. Mestre, Departamento de Agronomia, UEG. Avenida Brasil N° 435, CEP:75860-000, Quirinópolis, Go. Brasil, [semebber.lino@ueg.br](mailto:semebber.lino@ueg.br); ORCID (<https://orcid.org/0000-0002-2550-1325>)

### 1 RESUMO

A gestão eficiente da água é fundamental para a sustentabilidade na agricultura irrigada, exigindo tecnologias de monitoramento que aliem precisão e viabilidade econômica. Embora sensores de umidade do solo sejam essenciais, seu custo elevado dificulta a adoção em propriedades rurais menores. Este trabalho teve como objetivo desenvolver e calibrar um sensor de umidade de baixo custo como alternativa acessível. O protótipo foi construído com hastes de aço inox, um circuito oscilador CI555 e um microcontrolador ESP32, operando com base na variação de frequência influenciada pela constante dielétrica do solo. A calibração foi conduzida em laboratório, com 12 amostras de Latossolo Vermelho em diferentes níveis de umidade (de saturado a seco), com cinco repetições por ponto. A umidade gravimétrica foi determinada por secagem a 105 °C por 24 horas. Os resultados indicaram forte correlação linear entre as leituras do sensor e a umidade gravimétrica ( $R^2 = 0,9421$ ). A equação obtida foi  $Y = -0,0003 X + 0,3855$ , permitindo a conversão precisa das leituras. Conclui-se que o sensor desenvolvido representa uma solução eficaz e de baixo custo para o manejo otimizado da irrigação.

**Palavras-chave:** Agricultura de Precisão, Manejo da Água, Irrigação.

**OLIVEIRA, T. H.; PAULA, M. H. A.; SILVA, N. L.; PRADO, G. B.; LINO, S. S.  
DEVELOPMENT AND CALIBRATION OF A LOW-COST SOIL MOISTURE  
SENSOR WITH ESP32 FOR APPLICATION IN RED LATOSOLS**

## 2 ABSTRACT

Efficient water management is fundamental to sustainability in irrigated agriculture, requiring monitoring technologies that combine precision with economic viability. Although soil moisture sensors are essential, their high cost make them difficult to adopt on relatively small farms. The aim of this work was to develop and calibrate a low-cost moisture sensor as an affordable alternative. The prototype was built using stainless steel rods, a CI555 oscillator circuit and an ESP32 microcontroller, operating on the basis of frequency variation influenced by the soil's dielectric constant. Calibration was carried out in the laboratory with 12 samples of red latosol at different moisture levels (from saturated to dry), with five repetitions per point. Gravimetric moisture was determined by drying at 105 °C for 24 hours. The results indicated a strong linear correlation between the sensor readings and gravimetric humidity ( $R^2 = 0.9421$ ). The equation obtained was  $Y = -0.0003 X + 0.3855$ , allowing accurate conversion of the readings. It can be concluded that the developed sensor represents an effective, low-cost solution for optimized irrigation management.

**Keywords:** Precision Agriculture, Water Management, Irrigation.

## 3 INTRODUCTION

Irrigated agriculture plays a fundamental role in global food security. However, the pursuit of greater water use efficiency is becoming increasingly challenging in the face of climate variations and increasing water scarcity (O'Shaughnessy). *et al.* ., 2011; Silva *et al.*, 2017). In this context, accurate monitoring of soil moisture is essential for optimizing both water and energy use in irrigation systems (Vandôme). *et al.*, 2023).

Although the gravimetric method is considered the gold standard, its routine application is limited by its destructive and time-consuming nature. On the other hand, empirical evaluations lack precision (Pizetta, 2015; Jiménez, 2018). Electronic sensors have emerged as promising alternatives, offering continuous, real-time measurements and enabling process automation (Vilela *et al.*, 2015). However, their cost remains a barrier for many rural producers, especially small-scale producers (Oliveira, 2018; Gomes *et al.*, 2017).

In Brazil, the widespread occurrence of red latosols, whose characteristics directly interfere with water retention and

movement, reinforces the need for specific sensor calibrations to guarantee the reliability of irrigation management data (Santos *et al.*, 2018; Pizetta, 2015; Paris; Rosa, 2017).

Given this scenario, the present work aimed to develop and calibrate a low-cost soil moisture sensor. To this end, a prototype was built with readily available components, and a response curve adapted to the characteristics of the Red Latosol was defined.

## 4 MATERIALS AND METHODS

This study was conducted in the Multidisciplinary Laboratory and the Computer Laboratory of the State University of Goiás (UEG), Southwest Campus, located in the municipality of Quirinópolis, state of Goiás, during the first semester of 2025.

The development of the soil moisture sensor prototype was based on the ESP32 microcontroller, which was used as the central processing unit. To measure the water content, an oscillator circuit based on the 555 integrated circuit was incorporated into the system, along with resistors,

capacitors, and three 304 stainless steel rods with a diameter of 3.17 mm and a length of 65 mm, which act as sensing elements. The sensor's operation is based on the frequency variation generated by the circuit, which is directly influenced by the capacitance and resistance between the rods. These variations are a consequence of changes in the soil's dielectric constant, which is directly related to its moisture content. ESP32 programming was performed in C++ using the Arduino IDE platform.

The sensor was calibrated using samples of Red Latosol, which were

collected from the 0 to 20 cm depth layer on a rural property located near Quirinópolis. Granulometric analysis indicated that the soil contained 654.0 g kg<sup>-1</sup> of sand, 61.0 g kg<sup>-1</sup> of silt, and 285.0 g kg<sup>-1</sup> of clay and was classified as sandy loam. Physicochemical analyses, whose results are organized in Table 1, were performed at the Solotech Cerrado laboratory in Rio Verde - GO. To standardize the test conditions, all the samples were compacted to the same mass in containers of uniform volume, resulting in a soil density (Ds) of approximately 1.23 g cm<sup>-3</sup>.

**Table 1.** Chemical characteristics of the soil.

| <b>Prof.</b> | <b>P</b>            | <b>K</b>  | <b>Here</b>            | <b>Mg</b>  | <b>S</b>            | <b>Al</b>              | <b>H+Al</b>        | <b>pH</b>  |          |
|--------------|---------------------|-----------|------------------------|------------|---------------------|------------------------|--------------------|------------|----------|
| m            | mg dm <sup>-3</sup> |           | cmolc dm <sup>-3</sup> |            | mg dm <sup>-3</sup> | cmolc dm <sup>-3</sup> |                    | CaCl2      |          |
| 0.00-0.20    | 9.20                | 180.00    | 1.66                   | 0.57       | 7.00                | 0.60                   | 5.45               | 4.3        |          |
| <b>Prof.</b> | <b>In</b>           | <b>Zn</b> | <b>B</b>               | <b>Ass</b> | <b>Faith</b>        | <b>Mn</b>              | <b>MO</b>          | <b>CTC</b> | <b>V</b> |
| m            |                     |           | mg dm <sup>-3</sup>    |            |                     |                        | g dm <sup>-3</sup> | %          |          |
| 0.00-0.20    | 5.00                | 1.00      | 0.20                   | 2.40       | 41.70               | 87.00                  | 27.4               | 8.16       | 33.29    |

<sup>1</sup> Depth (Prof.); P and K extractor, Mehlich<sup>1</sup>; organic matter (OM); cation exchange capacity (CEC); base saturation percentage (V).

Twelve identical samples were prepared, broken up and air-dried, with moisture contents ranging from 0.120 g g<sup>-1</sup> to 0.330 g g<sup>-1</sup>. Ten intermediate points were obtained through the controlled addition of water. Sensor readings were taken every 5 seconds, with five repetitions per sample, and the data were recorded in spreadsheets. The reference gravimetric moisture content was determined by the oven drying method at 105 °C for 24 hours using a precision analytical balance. This method is widely recognized as the gold standard in the calibration of soil moisture sensors (Marcelino *et al.*, 2023).

To correlate the sensor readings with the values obtained through the gravimetric method, a simple linear regression model is applied. The quality of the fit and the sensor performance will be evaluated using the coefficient of determination (R<sup>2</sup>). All the statistical analyses, calibration curve fitting,

and graph creation will be performed using Microsoft Excel software.

## 5 RESULTS AND DISCUSSION

Calibration of the prototype soil moisture sensor revealed a consistent linear relationship between the values recorded by the ESP32 microcontroller and the gravimetric moisture of the Red Latosol, as shown in Figure 1. To represent this correlation, a simple linear regression model was applied, the fit of which resulted in the following equation:

$$Y = -0.0003 X + 0.3855 \quad (1)$$

In what way:

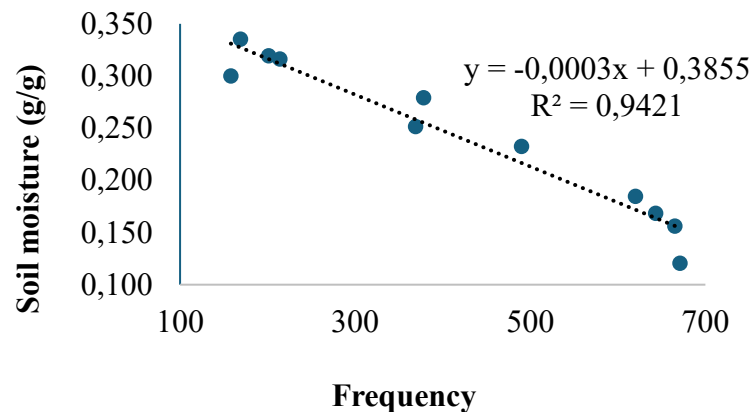
Y - gravimetric moisture content of the soil (g g<sup>-1</sup>);

X - sensor reading (scale from 0 to 1023).

The quality of the fit was confirmed by the high coefficient of determination ( $R^2$ ) obtained, which reached 0.9421. This means

that approximately 94.21% of the variation observed in gravimetric moisture can be directly explained by the readings provided by the sensor.

**Figure 1.** Calibration chart of the soil moisture sensor in Red Latosol.



The coefficient of determination obtained during the calibration ( $R^2 = 0.9421$ ) strongly indicates the high accuracy of the prototype, demonstrating its ability to accurately estimate soil moisture within the tested range ( $0.120 \text{ g g}^{-1}$  to  $0.335 \text{ g g}^{-1}$ ). This performance is comparable to, and in some cases even superior to, that of several low-cost moisture sensors and even commercial models. For example, Pizetta (2015) reported  $R^2$  values between 0.90 and 0.98 for capacitive sensors applied to different soil types, whereas Paris and Rosa (2017) achieved an  $R^2$  of 0.97 when a CS12 capacitive sensor specifically in a Red Latosol was used. Similarly, the studies by Oliveira (2018) and Gomes *et al.* (2017) obtained high coefficients of determination when working with affordable sensors, reinforcing the potential of low-cost solutions for soil moisture monitoring, which also validated the efficiency of this technology, reinforcing the potential of low-cost solutions for soil moisture monitoring.

The negative slope of the calibration line ( $a = -0.0003$ ) is aligned with the operating principle of capacitive sensors. In these cases, the increase in moisture, and consequently the increase in the dielectric constant of the soil, causes an inversely

proportional variation in the frequency or reading of the sensor, resulting in decreasing values as the soil becomes more humid.

In addition to its accuracy, the simplicity of the prototype's construction and its integration with the ESP32 microcontroller make this solution especially promising for applications on small and medium-sized farms. In these contexts, where resources for acquiring more advanced technologies may be limited, tools such as this can significantly assist in more efficient irrigation management. Another positive point is the use of 304 stainless steel rods, which contribute to the sensor's durability in contact with the soil, reducing the corrosion problems common in resistive sensors with copper rods, as evidenced by Pinto, Vilas Boas and Silveira (2017).

However, it is important to highlight that the calibration was performed under controlled conditions and for a specific type of soil (red latosol). The response of moisture sensors can vary according to characteristics such as texture, salinity, and apparent density of the soil (Pizetta, 2015). Therefore, future studies should focus on validating the sensor in the field, encompassing different soil classes, varying

salinity conditions, and analyses of its stability and durability over time.

## 6 CONCLUSION

The prototype soil moisture sensor, developed with low-cost components and using the ESP32 microcontroller, proved to be an efficient solution for monitoring soil water. During laboratory tests carried out with Red Latosol, a strong correlation was observed between the sensor readings and the actual soil moisture measured by the gravimetric method. This correlation had a high coefficient of determination ( $R^2 = 0.94$ ), indicating high data reliability. The obtained calibration equation ( $Y = -0.0003X + 0.3855$ ) allows the electronic readings to be converted into practical moisture values, facilitating proper irrigation management. Therefore, the sensor stands out as an economical and technically viable alternative, especially for small and medium-sized producers, contributing to the automation of irrigation systems and more efficient water use in agriculture.

## 7 ACKNOWLEDGEMENTS

The authors thank the Vice-Rectorate for Research and Graduate Studies (PRP) of UEG for its institutional support and the PRP Pro-Events for the financial support that made the presentation of this work possible.

## 8 REFERENCES

- GOMES, FHF; CUNHA, FN; LOPES FILHO, LC; VIDAL, VM; TEIXEIRA, MB; SOARES, FAL. Calibration of a low-cost soil moisture sensor. **Brazilian Journal of Irrigated Agriculture** , Fortaleza, v. 11, n. 4, p. 1509-1516, 2017.
- JIMÉNEZ, ALAC. **Calibration of the YL-69 soil moisture sensor for irrigation management**. 2018. Dissertation. (Master's Degree in Agricultural Engineering) – Federal Rural University of Pernambuco, Recife, 2018.
- MARCELINO, AS; DELMOND, JG; COSTA, AR; SILVA, PC. Calibration of resistive sensors for determining soil water content and automating an irrigation system. *In* : NATIONAL CONGRESS ON IRRIGATION AND DRAINAGE, 32nd, 2023, Fortaleza. **Proceedings** [...]. Viçosa: Brazilian Society of Irrigation and Drainage, 2023. p. 1-11.
- O'SHAUGHNESSY, SA; HEBEL, MA; EVETT, SR; COLAIZZI, PD Evaluation of a wireless infrared thermometer with a narrow field of view. **Computers and Electronics in Agriculture** , New York, v. 76, p. 59-68, 2011.
- OLIVEIRA, CL **Calibration of low-cost soil moisture sensors** . Undergraduate Thesis (Bachelor's Degree in Agricultural Engineering) - Federal Rural University of Pernambuco, Garanhuns, 2018.
- PARIS, LA; ROSA, HA **Calibration of CS12 capacitive soil moisture sensor in Dystrophic Red Latosol** . 2017. Undergraduate Thesis (Agronomy) – Centro Universitário da Fundação Assis Gurgacz, Cascavel, 2017.
- PINTO, JJ; VILAS BOAS, MA; SILVEIRA, VF. **Correlation between low-cost soil moisture sensor and TDR** . 2017. Undergraduate Thesis (Agricultural Engineering) – State University of Western Paraná, Cascavel, 2017.
- PIZETTA, SC **Calibration of capacitance sensors (FDR) for estimating moisture in different soils 2015**. 2015. Dissertation (Master's in Water Resources in

Agricultural Systems) – Federal University of Lavras, Lavras. 2015.

SANTOS, HG JACOMINE, PKT ANJOS, LHC OLIVEIRA, VA LUMBRERAS, JF COELHO, MR ALMEIDA, J. Á. ARAÚJO FILHO, JC OLIVEIRA, JB & CUNHA, TJ F . **Brazilian Soil Classification System** . 5th ed. rev. and enlarged . Brasília, DF: Embrapa , 2018.

VANDÔME, P.; LEAUTHAUD, C.; MOINARD, S.; SAINLEZ, O.; MEKKI, I.; ZAIRI, A.; BELAUD, G. Making

technological innovations accessible to agricultural water management: Design of a low-cost wireless sensor network for drip irrigation monitoring in Tunisia. **Smart Agricultural Technology** , Tunisia , v. 4, article 100227, p. 1-11, 2023.

VILELA, M. da S.; CABRA FILHO, FR; TEIXEIRA, MB; AMARAL, AM; VELLAME, LM; SOARES, FAL. Accuracy of a low-cost electronic weighing mini-lysimeter . **Irriga**, Botucatu, v. 1, n. 2, p. 158-167, 2015.