PERFORMANCE OF MOISTURE SENSORS IN SALT-AFFECTED SOILS

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ABSTRACT: Monitoring soil moisture is key to efficient irrigation and reducing water and energy waste, especially in saline soils. This study assessed two indirect methods for estimating soil moisture: a low-cost resistive sensor (YL-69) and a tensiometer, under varying electrical conductivity (EC) levels in two experiments. In Experiment I, salinization was induced by capillary saturation with saline solutions ($0 – 16\ dS\ m^{-1}$). In Experiment II, salinity increased through irrigation with brackish water during beet cultivation ($0 – 8\ dS\ m^{-1}$). Sensor readings were compared to gravimetric soil moisture measurements and analyzed using regression models and statistical indices, including root mean square error, Willmott's agreement index, and the confidence index. Both sensors showed high correlations with actual soil moisture ($R^2 > 0.97$ for tensiometer and 0.94 for YL-69). Soil salinity had minimal impact on tensiometer readings (deviations $\leq 0.03\ m^3\ m^{-3}$), but significantly affected the YL-69 sensor (up to $0.13\ m^3\ m^{-3}$ without specific calibration). The study proposes YL-69 calibration and a model to estimate EC from electrical resistivity and soil moisture, enhancing its use in saline soils. Calibration of the YL-69 sensor for different salinity levels is deemed necessary.

KEYWORDS: resistive sensor; tensiometer; salinity.

DESEMPENHO DE SENSORES DE UMIDADE EM SOLOS AFETADOS POR SAIS

RESUMO: Monitorar a umidade do solo é essencial para irrigação eficiente e redução do desperdício de água e energia, sobretudo em solos salinos. Dois métodos indiretos de estimativa da umidade foram avaliados: um sensor resistivo de baixo custo (YL-69) e um tensiômetro, sob diferentes níveis de condutividade elétrica (CE), em dois experimentos. No Experimento I, a

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salinização foi induzida por saturação capilar (0 – 16 dS m⁻¹); no Experimento II, a salinidade aumentou via irrigação com água salobra durante o cultivo de beterraba (0 – 8 dS m⁻¹). As leituras dos sensores foram comparadas à umidade gravimétrica do solo e avaliadas por modelos de regressão e índices estatísticos, incluindo erro quadrático médio, índice de concordância de Willmott e índice de confiança. Os sensores apresentaram alta correlação com a umidade real ($R^2 > 0,97$ para o tensiômetro e $> 0,94$ para o YL-69). A salinidade teve impacto mínimo nas leituras do tensiômetro (desvios $\leq 0,03$ m^3 m^{-3}), mas afetou o YL-69 (até 0,13 m^3 m^{-3} sem calibração específica). Foram propostas equações de calibração e um modelo para estimar a CE com base na resistividade elétrica e umidade do solo, ampliando o uso do YL-69 em solos salinos. Sob diferentes níveis de salinidade a calibração do sensor YL-69 é necessária.

PALAVRAS-CHAVE: Sensor resistivo; tensiômetro; salinidade.

INTRODUCTION

Efficient soil moisture monitoring is fundamental for optimizing irrigation practices and reducing water and energy waste, particularly in environments affected by salinity. A variety of methods are employed for this purpose, including gravimetric, tensiometric, resistive, dielectric, and remote sensing techniques (Rasheed et al., 2022). However, the accuracy of these methods can be significantly influenced by the physical and chemical properties of the soil, with electrical conductivity and salinity standing out as key factors (Peng et al., 2022).

Saline soils are widespread in arid and semi-arid regions, affecting over one billion hectares globally (FAO, 2020). In these areas, irrigation is essential to meet crop water requirements (Rodrigues et al., 2022), but water sources often contain high salt concentrations, which can exacerbate soil salinization when mismanaged (Castro & Santos, 2020). In Brazil, the semi-arid Northeast, including irrigated perimeters, is particularly affected (Pessoa et al., 2022). Given that agriculture is the largest consumer of freshwater, accurate soil moisture monitoring is crucial for optimizing water use and improving energy and fertilizer efficiency (FAO, 2020; KC et al., 2021).

Among the available technologies, low-cost sensors such as resistive and tensiometric models present attractive, accessible options for practical irrigation management. Resistive sensors operate by detecting changes in electrical resistance, which decreases as soil water content increases (Tan et al., 2019). Tensiometers, on the other hand, measure soil matric potential and are widely used in vegetable production systems, though their performance is limited to tensions below approximately 80 kPa (Marouelli, 2008).

Despite the growing interest in soil moisture sensing technologies and studies showing that low-cost resistive sensors can achieve results comparable to professional-grade devices (Jiménez et al., 2019), evaluations under saline conditions remain limited. Salinity can alter soil structure and hydraulic properties, potentially influencing tensiometer readings, and it directly affects resistive sensors by reducing soil electrical resistance, often leading to overestimation of water content (Adam et al., 2012). This underscores the need for calibration models that account for varying salinity levels, particularly for low-cost devices that could expand access to precision irrigation tools for smallholder farmers (Su et al., 2014).

This study aimed to evaluate the performance of a resistive sensor (YL-69) and a tensiometer under increasing salinity levels. Two experiments were conducted: one with salinization via capillary saturation (0 – 16 dS m^{-1}) and another during beet cultivation with irrigation water of varying salinity (0 – 8 dS m^{-1}). The objective was to assess the impact of salinity on sensor accuracy and propose correction equations for moisture estimation.

MATERIALS AND METHODS

Two experiments were conducted to evaluate the performance of two soil moisture sensors (YL-69 resistive and tensiometer) under different levels of electrical conductivity (EC). Both used the same soil type.

In Experiment I, soil columns were salinized via capillary saturation with brackish water with EC levels of 0, 2, 4, 8, and 16 dS m^{-1} and monitored for 23 days during natural drying. In Experiment II, beet plants were cultivated under irrigation with brackish water (EC: 0, 2, 4, 6, and 8 dS m^{-1}) for 50 days. Afterward, the sensors were installed, and moisture readings were taken for 55 days.

The experiments were conducted in a protected greenhouse environment at the Federal Rural University of Pernambuco (UFRPE), Recife Campus, located at 8°01′01″ S latitude and 34°56′41″ W longitude. The greenhouse was built at an altitude of 6.5 meters and featured lateral anti-aphid screens and a 150-micron diffuser plastic film as roofing. Its internal dimensions were 11 × 6 meters, totaling an area of 66 m^2.

Soil sampling was carried out in the 0 – 30 cm layer of a soil classified as Fluvent (Soil Survey Staff, 2022). The physical and chemical characteristics of the soil were determined

(Table 1). The soil used in both experiments was passed through a 4-mm mesh sieve to preserve its microaggregated structure.

Table 1. physical and chemical characterization of Fluvent used in the experiments.

physical characteristics								
Sand	Silt	Clay	WDC	dS	Pd	TP	DD	Textural Class
---------- g kg^{-1} ----------				--- g cm^{-3} ---		----- % -----		Silt loam
200	560	240	102	1.34	2.60	48.68	41.64	

chemycal characteristics										
EC_{se}	pH	Na^+	K^+	Ca^{2+}	Mg^{2+}	SB	H + Al	CEC	BS	ESP
dS m^{-1}	(1:2.5)	--------------------------- cmol$_c$ dm^{-3} ----------------------------							---- % ----	
1.39	5.76	0.57	0.40	11.68	3.90	16.54	3.07	19.61	84.33	2.68

dS = Density of the soil, Pd = Particle density, TP = Total porosity; WDC = Water-dispersible clay, DD = Dispersion degree. Exchangeable $Na+$ and $K+$ extracted by ammonium acetate and pH (1:2.5 $H2O$); exchangeable $Ca2+$, $Mg2+$, and $Al3+$ extracted in Mehlich; ECse = Electrical conductivity in saturation extract. ESP = Exchangeable sodium percentage; SB = Sum of bases; effective CEC = effective cation exchange capacity; BS = Base saturation.

The experimental design in both cases was a randomized block in a 5 × 2 factorial scheme (five EC levels × two sensor types), with four replicates. In Experiment I, soil columns (10 cm diameter × 15 cm height) were used. In Experiment II, 15 L pots filled with 11 L of soil (dry mass ≈ 17.6 kg) were used.

Gravimetric moisture was determined daily by weighing the pots and by oven-drying samples at 105 °C for 48 h. Volumetric moisture was calculated using soil bulk density. Readings from the YL-69 were obtained via microcontroller and converted into electrical resistance. Tensiometers were read with a digital puncture tensimeter. Soil moisture curves were developed for both methods.

Regression models were used to relate sensor readings with actual soil moisture, evaluated through coefficient of determination (R^2), root mean square error (RMSE), Willmott's agreement index (d), and the confidence index (c), as proposed by Camargo and Sentelhas (1997).

RESULTS AND DISCUSSION

Both sensors showed high correlation with gravimetric soil moisture in both experiments. For tensiometers, regression models reached $R^2 > 0.97$ regardless of salinity level, indicating low sensitivity to salinity. In contrast, the resistive sensor YL-69 showed greater variation with increasing electrical conductivity (EC), requiring separate calibration curves for each salinity level to achieve similar precision ($R^2 > 0.96$) (Table 2).

Table 2. Calibration Equations for the Tensiometer and YL-69 Sensor under Different Salinity Levels.

	Experiment I		**Experiment II**	
	YL – 69	**Tensiometer**	**YL-69**	**Tensiometer**
S0	$\theta = 0.6707e^{-0.0014x}$ $R^2 = 0.98$	$\theta = -0.049 \ln(x) + 0.6105$ $R^2 = 0.99$	$\theta = 0.9493e^{-0.0017x}$ $R^2 = 0.98$	$\theta = 3e{-}7x^2 - 0.0004x + 0.4622$ $R^2 = 0.98$
S1	$\theta = 0.6660e^{-0.0017x}$ $R^2 = 0.98$	$\theta = -0.050 \ln(x) + 0.6176$ $R^2 = 0.99$	$\theta = 0.9495e^{-0.0019x}$ $R^2 = 0.98$	$\theta = 3e{-}7x^2 - 0.0005x + 0.4564$ $R^2 = 0.98$
S2	$\theta = 0.9991e^{-0.0023x}$ $R^2 = 0.98$	$\theta = -0.042 \ln(x) + 0.5709$ $R^2 = 0.97$	$\theta = 0.8472e^{-0.0019x}$ $R^2 = 0.97$	$\theta = 3e{-}7x^2 - 0.0005x + 0.4853$ $R^2 = 0.98$
S3	$\theta = 0.8440e^{-0.0022x}$ $R^2 = 0.96$	$\theta = -0.044 \ln(x) + 0.5622$ $R^2 = 0.99$	$\theta = 1.1133e^{-0.0027x}$ $R^2 = 0.98$	$\theta = 3e{-}7x^2 - 0.0005x + 0.4765$ $R^2 = 0.98$
S4	$\theta = 0.9296e^{-0.0028x}$ $R^2 = 0.96$	$\theta = -0.046 \ln(x) + 0.5745$ $R^2 = 0.98$	$\theta = 1.0402e^{-0.0027x}$ $R^2 = 0.98$	$\theta = 3e{-}7x^2 - 0.0005x + 0.4816$ $R^2 = 0.98$

S0, S1, S2, S3, and S4 are equivalent to EC levels of 0, 2, 4, 8, and 16 dS m-1 in the experiment with soil columns (Experiment I) and 0, 2, 4, 6, and 8 dS m-1 for the experiment with the pots irrigated with brackish water (Experiment II).

The influence of salinity was more pronounced in the YL-69 sensor due to its operating principle based on electrical resistance, which is affected by ion concentration in the soil solution (Rasheed et al., 2022). As salinity increased, electrical resistance decreased, leading to overestimation or underestimation of moisture if calibration was not adjusted. Tensiometers, due to their physical principle, were not significantly affected by salt concentration, with a maximum deviation of 0.03 $m^3 m^{-3}$ in both experiments.

Statistical indices confirmed the accuracy of both sensors when properly calibrated. For the YL-69, RMSE values ranged from 0.01 to 0.03, while the Willmott agreement index (d) was above 0.98 in all cases. The performance index (c) also indicated high predictive ability ($c > 0.95$) (Table 2). These results extend the good performance previously observed under non-saline conditions (Jiménez et al., 2019), demonstrating that, with proper calibration, low-cost sensors can also perform well in saline environments (Table 3).

Table 3. Statistical indices of the tensiometer and the YL-69 sensor in salinized soil.

	Experiment I						**Experiment II**					
	RMSE		**Willmott (d)**		**Performance (c)**		**RMSE**		**Willmott (d)**		**Performance (c)**	
	Tens	**YL**	**Tens**	**YL**	**Tens**	**YL**	**Tens**	**YL**	**Tens**	**YL**	**Tens**	**YL**
S0	0.01	0.01	1.00	1.0	0.99	0.99	0.02	0.02	0.98	0.99	0.97	0.98
S1	0.01	0.02	1.00	0.99	0.99	0.98	0.01	0.02	0.99	0.99	0.98	0.98
S2	0.01	0.03	0.99	0.98	0.98	0.97	0.01	0.03	1.00	0.98	0.99	0.97
S3	0.01	0.02	1.00	0.99	0.99	0.98	0.03	0.02	0.95	0.99	0.94	0.98
S4	0.01	0.02	1.00	0.99	0.99	0.97	0.01	0.02	1.00	0.99	0.99	0.98

S0, S1, S2, S3, and S4 are equivalent to EC levels of 0, 2, 4, 8, and 16 dS m-1 in the experiment with soil columns (Experiment I) and 0, 2, 4, 6, and 8 dS m-1 for the experiment with the pots irrigated with brackish water (Experiment II).

A comparison between field capacity estimates using tensiometers and YL-69 sensors revealed that applying calibration equations developed for non-saline conditions to saline soils could result in errors of up to 26%. Conversely, using equations from saline treatments in non-saline conditions led to overestimations of up to 31%. This highlights the importance of specific calibration curves for different salinity scenarios (Peng et al., 2022).

Finally, a multiple regression equation was developed to estimate soil EC using the YL-69 sensor based on electrical resistance and volumetric moisture. The model achieved $R^2 = 0.95$ for moisture values between 0.10 and 0.15 $m^3\ m^{-3}$ (Figure 1).

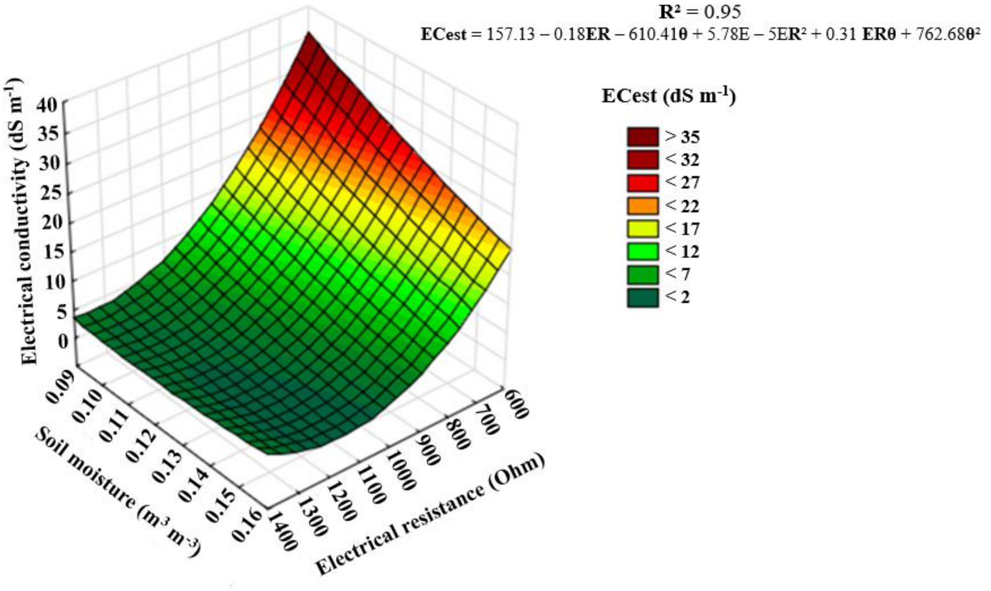

Figure 1. Electrical conductivity of the soil saturation extract estimated using the electrical resistance of YL 69 and volumetric soil moisture. ECest = Estimated electrical conductivity of the soil, ER = electrical resistance; θ = volumetric soil moisture.

The estimation of EC is already a common practice using soil sensors with different operational principles, as evidenced by the use of TDR and 5TE sensors. The operating principle of TDR involves reflectometry in the time domain, which can also include electrode adaptations to enhance the estimation of the EC (Moret-Fernández et al., 2012). The 5TE is a capacitive sensor/reflectometry in the frequency domain (FDR), which is capable of estimating apparent EC of the soil. However, there are limitations to its use (Visconti et al., 2014). One potential solution is the use of a resistive sensor, such as YL-69, which could provide a new and low-cost alternative.

Despite the promising results obtained in the present study, further studies are necessary to obtain data on a wider range of soils, with varying chemical and physical characteristics, in order to support the further development of the low-cost sensor YL- 69. It is possible that adaptations of its components may even be necessary.

CONCLUSIONS

Soil salinity did not affect soil determination with tensiometers, thus allowing them to be used for indirect soil moisture determination regardless of the EC of the soil. In contrast, soil salinity can interfere with accurate soil moisture measurements with a resistive sensor such as the YL-69. However, accurate soil moisture data can be acquired with a resistive sensor such as the YL-69 under different soil EC levels to 30 dS m-1, but it must be calibrated to EC level of the saturation extract.

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