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TDR probe calibration methods for bulk electrical conductivity in two soil types

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ABSTRACT

Time Domain Reflectometry (TDR) stands out among the techniques used for determining volumetric soil water content (θ) and monitoring bulk electrical conductivity (ECb). However, the accuracy of TDR in measuring solute concentrations strongly depends on the adequacy of the calibration procedure employed. Therefore, this study adjusted models to determine the bulk electrical conductivity (ECb) of the soil solution as a function of the TDR-measured bulk electrical conductivity (ECb). The study was carried out at Embrapa Cassava and Tropical Fruits, located in Cruz das Almas, Bahia, Brazil, using a PCTDR version 4.0® (Campbell Scientific) and two calibration methodologies. The Giese–Tiemann constant was determined through readings of different levels of electrical conductivity using potassium nitrate as the solute in: (i) soil samples with sandy loam and loam–sandy clay textures saturated with potassium nitrate solution, and (ii) pure and commercial potassium nitrate solutions. ECb measurements were obtained either using the TDR probe directly connected to the device or coupled via electromechanical multiplexers. To verify the accuracy and validate the constants obtained from linear regression, the following statistical indices were applied: R^2 (coefficient of determination), RMSE (root mean square error), d (Willmott's index of agreement), and GSD (general standard deviation). The technique used to measure electrical conductivity did not directly affect the determination of the Giese–Tiemann constant. However, soil type, solute solution, and calibration methodology influenced the determination of this constant.

Keywords: Geise and Tieman constant, salinity monitoring, time domain reflectometry.

Métodos de calibração da sonda TDR para condutividade elétrica aparente em dois tipos de solo

RESUMO

A Reflectometria no Domínio do Tempo (TDR) se destaca entre as técnicas utilizadas para a determinação do conteúdo volumétrico (θ) de água e monitoramento da condutividade elétrica aparente (CEa) dos solos. Todavia, o desempenho da TDR para medir com precisão concentrações de solutos depende fortemente da adequação do procedimento de calibração em uso. Assim, objetivou-se com esse estudo o ajuste de modelos para a determinação da CEa da solução em função da CEa aparente da TDR. O estudo foi realizado na Embrapa Mandioca e Fruticultura, localizada no município de Cruz das Almas-BA. Usou-se o PCTDR versão 4.0 ® Campbell Scientific, e duas metodologias de calibração, sendo a constante de Giese-Tieman foi determinada através de leituras de diferentes níveis de condutividade elétrica considerando o soluto, o nitrato de potássio em: (i) amostras de solo de textura areia franca e franco argilo arenoso saturadas em solução de nitrato de potássio e também (ii) em solução do soluto PA e comercial , essas medidas da CEa foram realizadas utilizando a sonda conectada diretamente ao equipamento de TDR ou com acoplamento a multiplexadores eletromecânicos. Para verificar a acurácia e validação das constantes obtidas na regressão linear, aplicou-se os índices estatísticos: o R^2 (coeficiente de determinação), *RMSE* (raiz quadrada da média dos quadrados dos erros), "d" (índice de concordância de Willmott) e o desvio padrão geral (GSD). A técnica utilizada para medir a condutividade elétrica não influenciou diretamente no processo de determinação da constante de Giese-Tieman. O tipo de solo, a solução do soluto e metodologia de calibração influenciam na determinação da constante de Giese-Tieman.

Palavras-chave: constate de Geise e Tieman, monitoramento da salinidade, reflectometria no domínio do tempo.

1. INTRODUCTION

In agriculture, both irrigation practices and fertilizer application have evolved over time, contributing to stable crop productivity. Knowledge of volumetric soil water content is essential for any study involving irrigation water management. Moreover, the monitoring of soil bulk electrical conductivity (ECb) and soil solution electrical conductivity (ECw) has become increasingly important in studies focused on salinity control (Santana *et al.*, 2007; Santos *et al.*, 2010; Conceição *et al.*, 2017). The ECb measured by these sensors is highly correlated with the electrical conductivity measured in laboratory conditions (Sudduth *et al.*, 2005).

Electrical conductivity represents the ability of a material to conduct an electric current (Wang *et al.*, 2021; Wilson *et al.*, 2024; Horváth *et al.*, 2024). Instruments used to measure bulk soil electrical conductivity are based either on contact techniques, generating an electric current through insulated electrodes, or on electromagnetic induction, a non-contact method that induces current through a magnetic field and allows for non-destructive soil sampling (Molin and Rabelo, 2011).

Among existing techniques for measuring soil electrical conductivity, Time Domain Reflectometry (TDR) has been widely accepted in solute transport studies, primarily because of its ability to measure both water content and soil salinity in relatively large, undisturbed sampling volumes with a single probe and in very short time intervals (Santos *et al.*, 2012; Comegna *et al.*, 2022). On the other hand, the accuracy of TDR in measuring solute concentrations depends on the adequacy of the calibration procedure used (Capparelli *et al.*, 2018; Mane *et al.*, 2024).

Measuring electrical conductivity using TDR requires knowledge of impedance since the amplitude of the reflected voltage depends on the electrical conduction between the probe rods (Campbell Scientific, 2021; Wang *et al.*, 2021). The presence of free ions in the soil solution results in attenuation of the reflected signal.

The probe can be connected directly to the TDR or coupled to an electromechanical multiplexer linked to a distribution multiplexer and then to the TDR unit. When probes are coupled to electromechanical multiplexers, signal disturbances may occur due to electromagnetic pulse attenuation in the multiplexer channels (Coelho *et al.*, 2006). Hence, calibration is necessary to ensure that the probe provides reliable measurements of both volumetric soil water content and bulk electrical conductivity (ECb), regardless of whether it is directly connected or coupled via multiplexers (Ižvolt *et al.*, 2016).

Studies on TDR equipment calibration for estimating electrical conductivity are not widespread among users, mainly because of the lack of detailed information in the literature describing their potential and limitations. The probe constant (Kp) is easily determined through calibration by immersing the probe rods in solutions of known electrical conductivity using analytically pure salts. Although this is the most common approach, it may not reflect field conditions since soil composition varies considerably.

Therefore, this study adjusted models to determine the bulk electrical conductivity (ECb) of the soil solution as a function of the bulk electrical conductivity (ECb) measured by TDR and to generate calibration models that result in the Giese–Tiemann constant (Giese and Tiemann, 1975), considering the TDR signal both in direct probe connection and when using multiplexers in sandy loam and loam–sandy clay soils, under two sample preparation methodologies.

2. MATERIAL AND METHODS

The experiment was conducted at Embrapa Cassava and Tropical Fruits, located in Cruz das Almas, Bahia, Brazil (12°40′12″ S, 39°06′07″ W, 220 m altitude). The local climate is classified as tropical humid (Af) according to Köppen (Alvares *et al.*, 2014), with average annual precipitation, temperature, and relative humidity of 1,131.17 mm, 24.5°C, and 80%, respectively (Guimarães *et al.*, 2018).

2.1. Bulk electrical conductivity

Both for aqueous solutions and soil samples, bulk electrical conductivity (ECb) was determined using Equation 1, proposed by Giese and Tiemann (1975):

$$ECb = \frac{K_P}{Z_C}\frac{1-\rho}{1+\rho} \qquad (1)$$

Where *ECb* = bulk electrical conductivity of the soil (dS m^{-1}); *Kp* = probe constant (dS Ω m^{-1}) determined experimentally; *Zc* = cable impedance (50 Ω); and *ρ* = reflection coefficient (dimensionless).

The data logger routine for electrical conductivity returns the ρ value, which must be multiplied by the slope coefficient Kp (Equation 1), also known as the probe constant, to obtain the bulk electrical conductivity value. This constant is included in the TDR configuration and must be determined experimentally due to variations in materials and manufacturing (Campbell Scientific, 2005).

The PCTDR software (version 4.0®, Campbell Scientific) was used to determine Kp experimentally for a three-rod stainless steel TDR probe. The probe had an effective rod length of 0.10 m, spacing of 0.017 m, resin coating of 0.05 m at the rod base, and a 3.50 m coaxial cable (50 Ω).

The software was configured with Kp = 1 to determine the slope (Kp = α) of the linear regression between ECw values measured using a benchtop conductivity meter in solutions

(0.25, 0.50, 1.00, 1.50, 2.00, 2.50 e 3.00 dS m^{-1}) and the corresponding TDR 100 measurements. This methodology follows Ponciano *et al.* (2011). Two calibration procedures were evaluated: (i) determination of Kp in solutions of potassium nitrate (analytical and commercial grades); and (ii) determination of Kp in soil samples saturated with potassium nitrate solutions of different concentrations.

2.2. Determination of the probe constant (Kp) using potassium nitrate solutions

The first calibration method, widely used in literature (Noborio, 2001), employed solutions of known electrical conductivity. Two potassium nitrate sources were used, analytical grade (PA) and commercial fertilizer, dissolved in distilled water to achieve ECb levels of 0.25, 0.50, 1.00, 1.50, 2.00, 2.50, and 3.00 dS m^{-1}, verified using a temperature-compensated benchtop conductivity meter. Bulk electrical conductivity (ECb) was then measured using the TDR, with Kp initially set to 1 in the configuration. Linear regression between the TDR-measured ECb and laboratory ECw values allowed calculation of the probe constant Kp (slope of the line). Measurements were made under four conditions: (i) readings with the probe directly connected to the TDR using analytical-grade potassium nitrate (PA); (ii) readings with the probe directly connected to the TDR using commercial potassium nitrate; (iii) readings with the TDR probe coupled to electromechanical multiplexers using analytical-grade potassium nitrate (PA); and (iv) readings with the TDR probe coupled to electromechanical multiplexers using commercial potassium nitrate.

2.3. Determination of Kp in soils saturated with potassium nitrate solution

In the second methodology, sandy loam and loam–sandy clay soils were used. Samples were collected in January 2020 and subjected to physical and chemical characterization (Table 1).

Table 1. Physical and chemical characteristics of the soils used for calibration.

Characteristics	Soils	
	Sandy loam	**Loam–sandy clay**
Soil bulk density (kg dm^{-3})	1.78	1.51
Sand (g kg^{-1})	813.00	589.00
Silt (g kg^{-1})	96.00	72.00
Clay (g kg^{-1})	91.00	339.00
Macroporosity (%)	10.90	9.56
Microporosity (%)	14.10	25.04
Total porosity (%)	25.00	34.60
pH in water	7.40	5.80
P (mg dm^{-3})	19.00	7.00
K ($cmol_c$ dm^{-3})	0.05	0.21
Ca ($cmol_c$ dm^{-3})	2.25	1.78
Mg ($cmol_c$ dm^{-3})	0.32	1.00
Al ($cmol_c$ dm^{-3})	0.00	2.78
Na ($cmol_c$ dm^{-3})	0.06	0.33
H+Al ($cmol_c$ dm^{-3})	0.00	2.20
SB ($cmol_c$ dm^{-3})	2.68	3.32
CEC ($cmol_c$ dm^{-3})	2.68	5.52
V (%)	100.00	60.00
OM (g kg^{-1})	6.00	10.00

Note: P: phosphorus; K: potassium; Ca: calcium; Mg: magnesium; Al: aluminum; Na: sodium; H: hydrogen; SB: sum of bases; CEC: cation exchange capacity; V: base saturation; OM: organic matter.

The soil material was crumbled, sieved through a 2 mm mesh, and packed into PVC columns measuring 0.150 m in height and 0.075 m in diameter, resulting in a total of fourteen columns. The base of each soil column was sealed with a fine plastic mesh screen. After packing, the soils were leached continuously with distilled water to reduce soil bulk electrical conductivity (ECb) as much as possible, allowing the leaching of salts from the soil solution until reaching 0.030 dS m^{-1}. The samples were then oven-dried in a forced-air chamber at 65°C until constant mass was achieved. Subsequently, the columns were saturated for 48 hours with commercial potassium nitrate solutions used for fertigation, dissolved in distilled water with known electrical conductivities for each treatment (0.25, 0.50, 1.00, 1.50, 2.00, 2.50, and 3.00 dS m^{-1}).

Bulk electrical conductivity (ECb) readings were obtained using TDR probes and the PCTDR software (version 4.0®, Campbell Scientific). As in the previous calibration procedure, one probe was connected directly to the TDR100 device, while another was connected through an electromechanical multiplexer, which served as an interface between the probe and the TDR. Thus, the probe constant was determined according to the Giese and Tiemann (1975) equation under four ECb reading conditions: L1 – readings with the probe directly connected to the TDR in sandy soil; L2 – readings with the probe directly connected to the TDR in clayey soil; L3 – readings with the TDR probe coupled to electromechanical and distributor multiplexers in sandy soil; and L4 – readings with the TDR probe coupled to electromechanical and distributor multiplexers in clayey soil. After each TDR measurement, a solution extractor was inserted at the same probe insertion point, and a pressure of 70 kPa was applied using a manual vacuum pump. Approximately 20 mL of soil solution was collected and its electrical conductivity (ECw) was determined using a benchtop conductivity meter.

2.4. Statistical analyses

To verify the accuracy and validate the constants obtained from linear regression, the following statistical indicators were applied: R^2 – coefficient of determination, RMSE – root mean square error, d – Willmott's index of agreement (Willmott, 1981), and GSD – general standard deviation. Except for R^2, these indices were calculated according to Equations 2, 3, and 4, respectively:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i-1}(O_i - E_i)} \tag{2}$$

$$d = 1 - \frac{\sum_{i=1}^{n}(O_i - E_i)^2}{\sum_{i=1}^{n}(|E_i - \bar{O}| + |O_i - \bar{O}|)^2} \tag{3}$$

$$GSD = \sqrt{\frac{\sum_{i=1}^{n}(E_i - \bar{O})^2}{n}} \tag{4}$$

Where: n = number of data points; O_i = observed value; E_i = estimated value; and $\bar{O}$ = mean of observed data.

To evaluate the accuracy of the estimated and measured values, the RMSE was used as a measure of the average magnitude of estimation errors, as reported by Santos *et al.* (2014). RMSE values are always positive and the closer to zero, the greater the model accuracy. When the GSD and d indices are jointly evaluated, model performance is considered good when GSD ≤ 0.10 and d ≥ 0.95, and poor when d < 0.90 or GSD > 0.20. Intermediate values represent acceptable performance (Fila *et al.*, 2003).

2.5. Comparison of Giese–Tiemann constant determination methodologies

After determining the Giese–Tiemann constants (Kp) using both calibration methodologies, validation was performed using the Kp values with the best performance, based on higher R^2, higher d, lower RMSE, and lower GSD. These constants were inserted into the PCTDR software configuration to estimate ECb values for probes directly connected to the TDR and for those connected through multiplexers, in both sandy and loam–sandy clay soils. Additionally, ECb readings were obtained using a benchtop conductivity meter with automatic temperature compensation to validate the models statistically.

3. RESULTS AND DISCUSSION

3.1. Kp constant of the probe in solutions with different potassium sources

The electrical conductivities measured by the benchtop conductivity meter and by the TDR, through the PCTDR software and multiplexers (Figure 1), resulted in linear equations with high coefficients of determination (R^2) for both analytical-grade (PA) and commercial potassium nitrate solutions. This confirms the linear relationship between the observed and estimated electrical conductivity values when using fertilizer-grade salts such as potassium nitrate. Figures 1C and 1D show that, with the use of multiplexers, the constant of the Giese–Tiemann (1975) model is altered, presenting higher values for both analytical-grade and commercial salts compared with readings obtained directly with the probe connected to the TDR device. The differences in Kp values obtained with direct readings on the TDR are greater than those obtained using multiplexers, particularly when commercial salt is used.

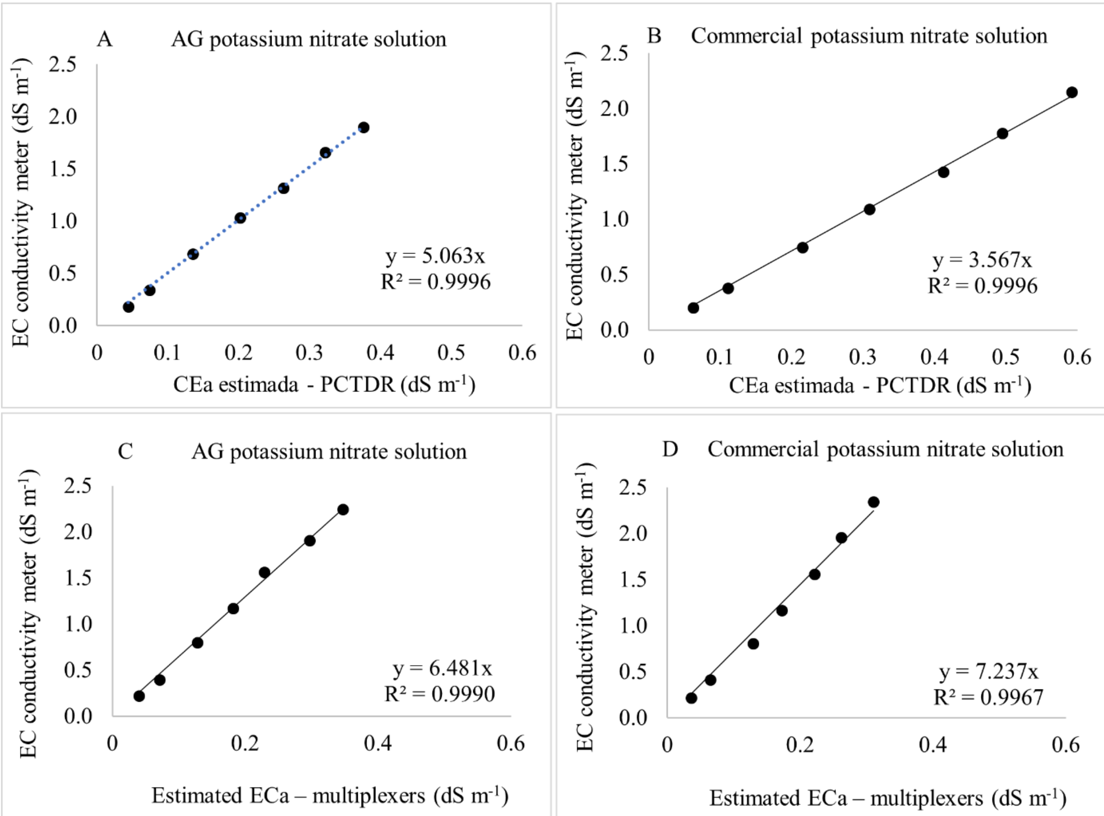

Figure 1. Regressions for obtaining the probe constants using (A) analytical-grade potassium nitrate (PA) solution; (B) commercial potassium nitrate with probes directly connected to the PCTDR; (C) analytical-grade and commercial potassium nitrate solutions; and (D) probes coupled to multiplexers.
Source: Authors.

Bulk electrical conductivity (ECb) increased linearly with the concentration of potassium nitrate for both analytical-grade reagents and commercial fertilizer, confirming that the availability of K^+ and NO_3^- ions in solution is directly proportional to the applied concentration. The curves exhibited similar slopes, indicating that the commercial fertilizer can be reliably used for agricultural management purposes, although small variations may arise from impurities present in its formulation (Mota *et al.*, 2021). This behavior highlights the usefulness of ECb as a practical parameter for estimating salt concentration in nutrient solutions, especially in fertigation and hydroponic systems, allowing greater efficiency in nutrient supply and reducing the risk of soil salinization (Souza *et al.*, 2022; Oliveira *et al.*, 2024; Tavares *et al.*, 2021).

The calculated values for the root mean square error (RMSE), Willmott's agreement index (d), and general standard deviation (GSD) of the equations for the readings performed with analytical-grade potassium nitrate, corresponding to constants of 5.06 and 6.48, fall within the range classified as good performance. This indicates excellent agreement between measured and estimated bulk electrical conductivity (ECb), mainly due to the high R^2 and d values (Table 2).

Table 2. Probe constant (Kp), root mean square error (RMSE), Willmott's index of agreement (d), general standard deviation (GSD), and coefficient of determination (R^2) under different solution and sensor conditions.

Solution and sensor conditions	Kp	RMSE	d	GSD	R^2
Potassium nitrate (PA) and probe in TDR	5.063	0.309	0.996	0.047	0.999
Commercial potassium nitrate and probe in TDR	3.566	0.632	0.975	0.076	0.999
Potassium nitrate (PA) and probe in multiplexer	6.481	0.566	0.993	0.068	0.997
Commercial potassium nitrate and probe in multiplexer	7.236	0.851	0.986	0.103	0.994

Source: Authors.

The most accurate model was obtained from direct readings with the TDR device using analytical-grade potassium nitrate (PA). The use of commercial potassium nitrate, by itself, reduces model accuracy, especially when multiplexers are used, as reflected by the higher RMSE values shown in Table 2. When multiplexers are connected, electrical conductivity readings become subject not only to the resistance of the medium but also to interferences arising from the shared grounding of multiple channels (Castiglione *et al.*, 2006).

3.2. Probe Kp constants in saturated soils under different potassium concentrations

The bulk electrical conductivity (ECb) values obtained from probes connected to multiplexers were lower than those from probes directly coupled to the PC-TDR device for both soil types saturated with commercial potassium nitrate solution (Figure 2). This reduction is attributed mainly to signal attenuation caused by longer cable lengths and the internal resistance of the multiplexer circuits.

In the determination of the Giese–Tiemann (1975) constant (Kp) using the PC-TDR, Kp values of 21.98 were obtained for sandy soil and 16.18 for clayey soil. A similar pattern was observed for data collected through multiplexers, with Kp values of 35.46 for sandy soil and 24.12 for clayey soil. Differences in Kp between direct TDR coupling and multiplexer use can be explained by electrical signal attenuation due to additional channels and switching circuits. The difference in Kp between sandy and clayey soils is primarily due to the higher electrical conductivity of sandy soil saturated with potassium nitrate solution, which leads to greater signal attenuation. Another contributing factor is that potassium nitrate solution in sandy soil, being chemically more inert, retains a greater number of ions in solution than clayey soil, where ion adsorption, precipitation, and the influence of the diffuse double layer reduce the concentration of ions in the soil solution (Silva *et al.*, 2018).

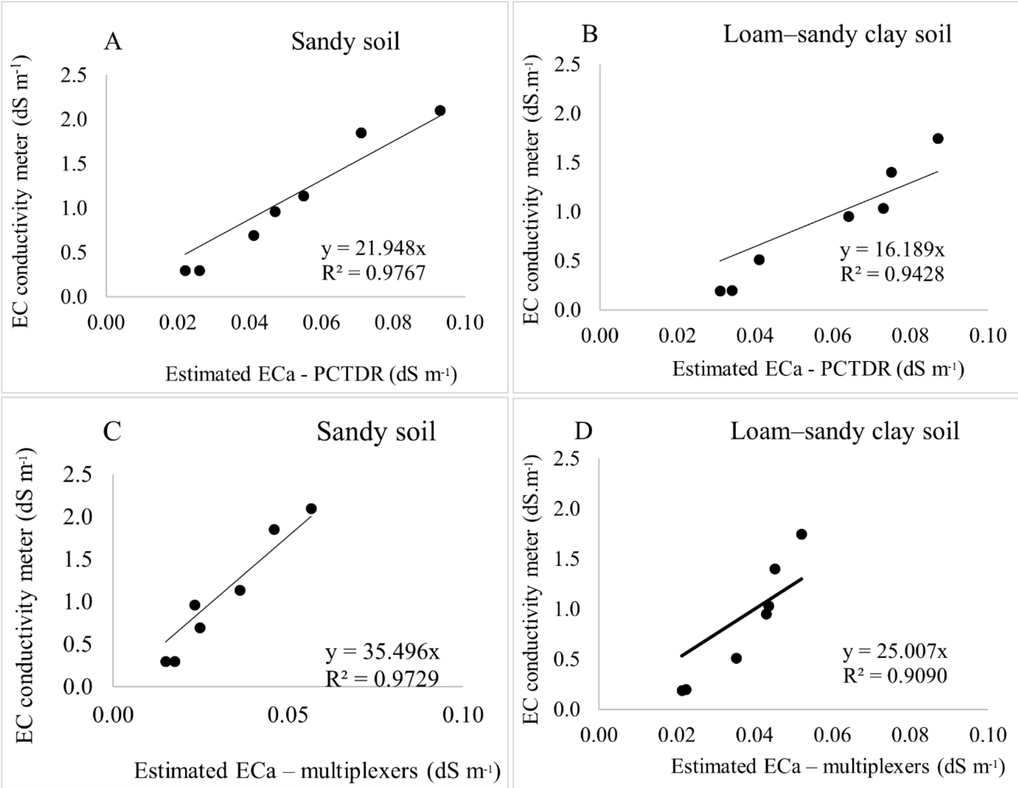

Figure 2. Regressions for obtaining the Giese–Tiemann constants using probes connected directly to the TDR in sandy soil (A) and clayey soil (B), and using probes coupled to multiplexers in sandy soil (C) and clayey soil (D).
Source: Authors.

The highest coefficients of determination (R^2) or best fits between measured and estimated ECb values were found for sandy soil, both with probes directly connected to the TDR and when using multiplexers with the PC-TDR. However, the accuracy indices (Table 3) clearly demonstrate that ECb readings obtained without multiplexers are more precise than those obtained through multiplexers.

Table 3. Probe constant (Kp), root mean square error (RMSE), Willmott's index of agreement (d), general standard deviation (GSD), and coefficient of determination (R^2) under different soil and sensor conditions.

Soil and sensor conditions	Kp	RMSE	d	GSD	R²
Sandy soil and probe in TDR	21.948	1.18	0.83	0.16	0.917
Clayey soil and probe in TDR	16.189	0.96	0.83	0.15	0.802
Sandy soil and probe multiplexer	35.496	1.18	0.70	3.40	0.904
Clayey soil and probe multiplexer	24.120	0.96	0.68	2.25	0.614

Source: Authors.

Except for the higher R^2 values in sandy soil, the other indices (RMSE, d, and GSD) did not show relevant differences (Table 3). Higher Kp values corresponded to higher measured ECb values, indicating greater apparent conductivity in sandy soil. This can be explained by the uniform distribution of moisture and salts in saturated sandy soil. Although clayey soils are typically better electrical conductors than sandy soils within the soil solution of a porous medium (Molin and Rabello, 2011; Machado *et al.*, 2006), factors such as pore size distribution, tortuosity, and electrochemical reactions affect ion movement and reduce effective ion concentration due to adsorption or precipitation.

It is also important to note that when probes are connected through electromechanical multiplexer channels, limitations can arise from noise and electromagnetic interference at the multipliplexer that affects the amplitude of the reflected signal in the TDR signal, reducing estimation reliability (Castiglione *et al.*, 2006; Coelho *et al.*, 2006). These may increase signal attenuation and impedance mismatches, reducing waveform quality and, consequently, the accuracy of bulk electrical conductivity (ECb) estimates. Similar findings were reported by Autovino *et al.* (2026). Who emphasized that an accurate soil electrical conductivity measurement requires careful calibration and validation of the TDR system under field conditions. Therefore, the present results indicate that direct probe connections provide more reliable ECb measurements than multiplexed systems, particularly when high accuracy is required for monitoring soil salinity and irrigation management. This explains the lower R^2 values observed under the conditions of probes coupled to multiplexers.

3.3. Comparison of methodologies

Under Methodology 1, the constants selected were 5.063 (for readings with the probe connected directly to the TDR using analytical-grade potassium nitrate) and 6.48 (for readings with the probe connected through the multiplexer using the same solution) (Table 2). Under Methodology 2, the selected constants were 16.189 (for direct readings of TDR in soil saturated with commercial potassium nitrate solution) and 24.12 (for readings using a multiplexer in loam–sandy clay soil) (Table 2).

For sandy soil, with the waveguide connected to the multiplexer–TDR system, the constant showing the highest accuracy was 24.120, corresponding to the lowest RMSE and GSD values, with the most notable difference for RMSE. Conversely, for loam–sandy clay soil, the waveguide directly connected to the TDR resulted in a constant of 16.189, also associated with smaller accuracy indices (Table 4). These constants indicate that ECb in sandy soil was 1.42 times higher than in clayey soil for the same TDR-measured value. Both Kp values are from Methodology 2, with soil samples saturated with commercial potassium nitrate—24.12 with multiplexer use in sandy soil and 16.189 without multiplexer use in loam–sandy clay soil. Methodology 2 yielded greater accuracy with direct TDR–probe readings in sandy soil (Kp = 16.189) compared with Methodology 1. For loam–sandy clay soil using multiplexers, Methodology 1 (Kp = 6.481) should be applied, as it provided better accuracy and model fit than Methodology 2. These results demonstrate that Methodology 2 is more suitable for sandy soil under both multiplexer use and direct TDR readings, whereas Methodology 1 is more appropriate for loam–sandy clay soil when using multiplexers and for estimating Kp from commercial potassium nitrate solution. For individual soil moisture readings in loam–sandy clay soil, Methodology 2, using direct probe–TDR readings in soil saturated with commercial potassium nitrate, is recommended (Table 4).

Table 4. Root mean square error (RMSE), Willmott's index of agreement (d), and general standard deviation (GSD) values for comparison of constants in sandy and loam–sandy clay soils, obtained from direct TDR readings (probe–TDR) and through multiplexers (probe–multiplexer–TDR).

	Sandy soil				**Loam–sandy clay soil**			
	Methodology 1		Methodology 2		Methodology 1		Methodology 2	
	Direct	Mult.	Direct	Mult.	Direct	Mult.	Direct	Mult.
Constants (Kp)	5.063	6.481	16.189	24.120	5.063	6.481	16.189	24.120
RSME	1.510	1.420	0.740	0.250	1.100	0.970	0.490	0.760
d	0.890	0.910	0.980	0.990	0.930	0.930	0.990	0.980
GSD	0.130	0.120	0.060	0.020	0.110	0.090	0.040	0.077

Source: Authors.

Although the conventional method for determining the Giese–Tiemann constant involves using distilled water and analytical-grade potassium nitrate (PA), the constants obtained through soil columns with commercial fertilizer solutions showed better performance, as evidenced by the statistical indicators.

4. CONCLUSIONS

The methodology used to measure electrical conductivity directly influences the determination of the Giese–Tiemann constant. Both methodologies, using TDR probes in commercial potassium nitrate solution and in soil saturated with the same solution, proved to be viable for estimating the bulk electrical conductivity of the soil.

5. DATA AVAILABILITY STATEMENT

Data availability not informed.

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