

Article

ECWS: Soil Salinity Measurement Method Based on Electrical Conductivity and Moisture Content

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Abstract: A novel method, ECWS, is proposed for measuring soil initial salinity content (b), based on the soil electrical conductivity EC and soil moisture content WS. This pioneering model rigorously establishes and incorporates the inherent potential correlation among soil bulk conductivity (EC_a), soil solution conductivity (EC_w), volume water content (θ_c), and soil salinity content (SSC). First of all, in order to delve the deeper relationship between EC_a , EC_w , θ_c and SSC, the soil salinity conductivity conversion coefficient ρ_a and soil leaching solution salinity conductivity conversion coefficient ρ_w were employed based on the formula of parallel conducting channels of the soil–water system, and a new measurement model of salinity content was constructed. After that, a mathematical analysis method was used to transform the coefficients of multiple sets of regression equations into matrices to solve ρ_a , ρ_w and b . Finally, to validate the accuracy of the proposed ECWS method, verification tests were conducted by utilizing TDR and PWMER sensors. The results with different salinity contents showed that the b size obtained by ECWS model were K_2SO_4 (1.84 g/kg), NaCl (1.91 g/kg), and KCl (1.92 g/kg). The maximum deviation was less than 0.08 g/kg (relative error less than 5%). The results showed that the influence of different anions and cations on the measurement of salinity content Cl^- is greater than that of SO_4^{2-} , and K^+ is greater than that of Na^+ . This study revealed the relationship between soil electrical conductivity and soil salinity content to a certain extent, and realized the transformation between them, which provided a new method for the measurement of soil salinity content, and also provided a reference for related research on the measurement of soil salinization.

Keywords: soil salinity content; soil solution conductivity; soil bulk conductivity; moisture content



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1. Introduction

Soil salinity content (SSC) is the total concentration of soluble salts in the soil solution in a certain volume of soil [1,2]. When the soluble salt content in the soil is too high, crops will have difficulty absorbing the necessary nutrients and water from the soil, thereby affecting the growth of crops. Continuous accumulation of soluble salt ions in the surface of the soil can lead to soil salinization. Therefore, analyzing SSC is of great importance for understanding the soil properties and formulating measures for improving saline–alkali soils [3].

Currently, the measurement methods of soil salinity content mainly include the mass method, model method, and conductivity method. The mass method mainly adopts the drying residue method and the sum of salt ion method. The drying residue method has high accuracy, but requires field sampling first, followed by a large amount of indoor analysis work, which is not suitable for rapid large-scale measurements. The sum of salt ion method mainly accumulates the content of all salt ions in the soil leachate, but the results may vary due to different analysis methods [4].

In addition, the model method uses mathematical methods to establish the SSC measurement model through simulation, simulation or remote sensing inversion. Some models, such as the salt transport model, the Hydrus-2D model [5], and the SWAP model [6], can simulate the SSC for a long time and across a wide range by inputting meteorological and soil parameters and other data, but due to the uncertainty of the model parameters, its errors continue to accumulate, which affects the accuracy of the simulation. In general, the remote sensing inversion method selects the relevant variables sensitive to SSC through spectral transformation and exponential screening, and performs model verification analysis [7,8]. Based on Sentinel-2A image technology, Wang [9] analyzed the spectral characteristics and parameters of SSC with different salinization soil degrees by using UAV cameras, and established an inversion model. Zhao [10] used UAV multispectral remote sensing data to construct an SSC inversion model based on support vector machine regression, random forest, and other machine learning algorithms, which provided technical support for the rapid monitoring and control of soil salinization in irrigation areas. Gao [11] verified and optimized the dielectric constant model of saline soil based on soil samples with different gradient moisture content and salinity, and established a remote sensing inversion model suitable for L-band microwave remote sensing. However, due to its discontinuity in time, it is difficult to obtain short-time interval remote sensing images due to the influence of natural conditions and satellite sensor types, which is not conducive to continuous long-term high-precision SSC monitoring research.

Soil water-soluble salt ions are strong electrolytes, and their conductivity can be expressed in terms of soil conductivity EC [12]. As a result, SSC can also be obtained by the conductivity method [13], which is relatively fast and can achieve long-term continuous SSC measurements without damaging the soil layer. Based on soil sensors and the Hilhorst model, Bañón [14] measured the volumetric conductivity and pore water conductivity of the soil to assess the salinity index of the soil. Bughici [5] used Hydrus-2D to simulate the drip irrigation system based on the soil conductivity, which provided a reference for the SSC monitoring of the drip irrigation system. Xie [15] established a linear relationship between the apparent conductivity of the soil measured by EM38 and the conductivity of the soil solution measured in the laboratory, and analyzed the temporal and spatial variation of SSC in the Yangtze River Estuary. According to the soil texture, Hossain [16] measured the conductivity of soil solution and soil body using different water–soil ratios, and established a linear regression relationship to monitor SSC in a certain area. Ismayilov [17] used a 1:5 soil solution conductivity measurement method to explore the relationship between soil conductivity and total soluble salinity in eight classical salt separator types, which is of great significance for conductivity assessment of SSC in irrigated land. In summary, it is of great significance to establish the relationship between EC and SSC for rapid and effective measurement or evaluation of SSC.

Most studies measured SSC indirectly by soil conductivity, and the influence of soil moisture content (WS) on their EC and SSC measurements was not considered [18]. Therefore, based on the relationship between conductivity and moisture content in the parallel resistance method and the parallel conductive channel formula of the soil–water system [19,20], we propose a method and model for measuring soil salt content in ECWS based on conductivity (EC) and moisture content (WS) and based on mathematical modeling theory. In this model, the conversion coefficient ρ_a of soil salt content/conductivity and the conversion coefficient ρ_w of salt content/conductivity of soil extract are introduced. In addition, this model divides the total soil salt content into two parts: NaCl addition and soil initial salt content b , which can not only indirectly reflect the relationship between EC_a , EC_w , θ_c , and salinity, but also realize the measurement of b and the analysis of SSC temporal variation. This study can provide a theoretical basis for the measurement and monitoring of soil salinity. See Table 1 for terminology abbreviations.

Table 1. Terminology and abbreviations.

Terminology	Abbreviations
soil salinity content	SSC
soil electrical conductivity	EC
soil moisture content	WS
soil initial salt content	b
soil bulk conductivity	EC_a
soil solution conductivity	EC_w
volumetric water content	θ_c
salt addition	M_c
the measured value of SSC	SSC_R
the predicted value of SSC	SSC_P
the average of the SSC_R	$\overline{SSC}_R$
the average of SSC_P	$\overline{SSC}_P$
soil salinity conductivity conversion coefficient	ρ_a
soil leaching solution salinity conductivity conversion coefficient	ρ_w
the absolute error of $\overline{SSC}_R$ and $\overline{SSC}_P$	$ \overline{R}_c $

2. Materials and Methods

2.1. Soil Salinity Measurement ECWS Model

Soil salt content (SSC) is not only related to electrical conductivity (EC) but also to moisture content (WS) [19], while soil solution conductivity, soil conductivity, and moisture content are also coupled to a certain extent [21,22]. Therefore, based on the mathematical theory and soil physicochemical basis, the ECWS measurement model [23,24] is constructed as follows according to the formula of parallel conductive channels in the soil–water system:

$$SSC = M_c + b = \rho_a EC_a + \rho_w \theta_c EC_w \quad (1)$$

where SSC is the soil salt content, g/kg; b is the initial soil salt content, g/kg; EC_a is the soil conductivity, $\mu\text{S}/\text{cm}$; EC_w is the soil solution conductivity, $\mu\text{S}/\text{cm}$; M_c is the salt addition, g/kg; ρ_a is the soil salinity conductivity conversion coefficient, representing the conversion of soil salt content and soil body conductivity, mS/cm ; ρ_w is the soil leaching solution salinity conductivity conversion coefficient, representing the conversion of soil extract salt content and soil solution conductivity, mS/cm ; and θ_c is the volume water content, %.

In Equation (1), the measured value of SSC is SSC_R , and the predicted value of SSC is SSC_P , as shown in Equation (2).

$$\begin{cases} SSC_R = M_c + b \\ SSC_P = \rho_a EC_a + \rho_w \theta_c EC_w \\ |\overline{R}_c| = |\overline{SSC}_R - \overline{SSC}_P| \end{cases} \quad (2)$$

where $\overline{SSC}_R$ is the average of the SSC_R ; $\overline{SSC}_P$ is the average of SSC_P ; and $|\overline{R}_c|$ is the absolute error of $\overline{SSC}_R$ and $\overline{SSC}_P$, g/kg.

Equation (3) can be established from Equation (1).

$$M_c = \rho_a EC_a + \rho_w \theta_c EC_w - b \quad (3)$$

The M_c of the formula can be measured by an electronic balance. The EC_a and θ_c can be measured by the sensor. The EC_w can be measured by a conductivity meter by the extractor method [25,26]. Then, in Equation (3), only ρ_a , ρ_w , and b are unknown. When M_c , EC_a , θ_c , and EC_w measurements are sufficient, regression analysis can be used to solve for ρ_a , ρ_w , and b .

If M_c has n gradients, then there is Equation (4):

$$\begin{bmatrix} M_{c1} \\ M_{c2} \\ \vdots \\ M_{cn} \end{bmatrix} = \begin{bmatrix} EC_{a1} & \theta_{c1}EC_{w1} \\ EC_{a2} & \theta_{c2}EC_{w2} \\ \vdots & \vdots \\ EC_{an} & \theta_{cn}EC_{wn} \end{bmatrix} \begin{bmatrix} \rho_a \\ \rho_w \end{bmatrix}_{2 \times 1} - b \begin{bmatrix} 1 \\ 1 \\ \vdots \\ 1 \end{bmatrix}_{n \times 1} \quad (4)$$

Let $e_c = \hat{M}_c - M_c$, where $\hat{M}_c$ is the predicted value of M_c obtained using Equation (3). The square of the deviation $(e_c)^2$ can be calculated using Equations (5) and (6).

$$E = \begin{bmatrix} e_{c1} \\ e_{c2} \\ \vdots \\ e_{cn} \end{bmatrix}^2 = \left\{ \begin{bmatrix} \hat{M}_{c1} \\ \hat{M}_{c2} \\ \vdots \\ \hat{M}_{cn} \end{bmatrix} - \begin{bmatrix} EC_{a1} & \theta_{c1}EC_{w1} \\ EC_{a2} & \theta_{c2}EC_{w2} \\ \vdots & \vdots \\ EC_{an} & \theta_{cn}EC_{wn} \end{bmatrix} \begin{bmatrix} \rho_a \\ \rho_w \end{bmatrix} + b \begin{bmatrix} 1 \\ 1 \\ \vdots \\ 1 \end{bmatrix} \right\}^2 \quad (5)$$

$$\begin{aligned} E_{n \times 1} &= (\hat{M}_{c_{n \times 1}} - D_{n \times 2} P_{2 \times 1} + B_{n \times 1})^2 \\ \hat{M}_{c_{n \times 1}} &= \begin{bmatrix} \hat{M}_{c1} \\ \hat{M}_{c2} \\ \vdots \\ \hat{M}_{cn} \end{bmatrix}, D_{n \times 2} = \begin{bmatrix} EC_{a1} & \theta_{c1}EC_{w1} \\ EC_{a2} & \theta_{c2}EC_{w2} \\ \vdots & \vdots \\ EC_{an} & \theta_{cn}EC_{wn} \end{bmatrix} \\ P_{2 \times 1} &= \begin{bmatrix} \rho_a \\ \rho_w \end{bmatrix}, B_{n \times 1} = b \begin{bmatrix} 1 \\ 1 \\ \vdots \\ 1 \end{bmatrix} \end{aligned} \quad (6)$$

Equation (7) is obtained by finding the partial derivatives of ρ_a , ρ_w , and b in Equation (6).

$$\begin{cases} \frac{\partial E}{\partial \rho_a} = -2(\hat{M}_{c_{n \times 1}} - D_{n \times 2} P_{2 \times 1} + B_{n \times 1}) \bullet (EC_a)_{n \times 1} = 0 \\ \frac{\partial E}{\partial \rho_w} = -2(\hat{M}_{c_{n \times 1}} - D_{n \times 2} P_{2 \times 1} + B_{n \times 1}) \bullet (\theta_c EC_w)_{n \times 1} = 0 \\ \frac{\partial E}{\partial b} = -2(\hat{M}_{c_{n \times 1}} - D_{n \times 2} P_{2 \times 1} + B_{n \times 1}) = 0 \end{cases} \quad (7)$$

Ultimately, ρ_a , ρ_w , and b can be determined through regression analysis, enabling the calculation of SSC_R and SSC_P using Equation (2).

2.2. Experimental Design

The validation test area is located in the apple orchard of the tenth regiment (E 80°51', N 40°34') in Alar City, Xinjiang, which is characterized by sandy loam soil, and the region where it is located is situated in the extreme continental arid desert climate of the warm belt, which is an irrigated agricultural area with abundant light, low precipitation, strong evaporation, severe secondary salinization of soil, and poor ecological environment [27].

Since the surface 0~20 cm soil is the main tillage layer [28], which is the source of water and nutrient absorption by the soil [29,30], and with reference to other studies [31], the soil profile soils in this area were analyzed for salinization, and the deeper the soil profile, the lower the degree of salinization, and therefore the 0~20 cm soils are dominated by severe and moderate soil salinization. Therefore, in order to verify the correctness of the proposed ECWS method, the following experimental design was carried out using the surface 0~20 cm sandy soil as the research object, the TDR sensor and the PWMER sensor as the EC_a and θ_c test methods, respectively, and the conductivity instrument as the EC_w test method.

2.3. Experimental Treatment

2.3.1. TDR Sensors

(1) TDR sensor: The model is True TDR-315H, the power supply voltage is 3.5~15 VDC, the principle of TDR method [32,33] is used to measure the EC_a , the conductivity accuracy is $\pm 5\%$ $\mu\text{S}/\text{cm}$, and the measurement range is 0~20,000 $\mu\text{S}/\text{cm}$.

(2) Salt content design: According to the measurement range of the TDR sensor, the design salt content adopts NaCl (purity 99.9%), its addition amount (g/kg) is 0, 1.5, 3.0, 4.5, 6.0, 7.5, 9.0, 10.5, 12.0, 15.0, 18.0, and 21.0, a total of 12 levels, recorded as $M_{t-i}, i = 0, 1, 2, \dots, 11$.

(3) Moisture content design: In accordance with conditions favorable for crop growth, the correlation between soil moisture content and field capacity is considered. The design moisture content ranges from 10% to 70% of the field capacity of deionized water, with the soil moisture content conducive to the growth of most crops falling between 40% and 70% of the field capacity. Following the principle of 'sparse first, then dense', the moisture content is set at 10, 20, 30, 40, 45, 50, 55, 60, 65, and 70, totaling 10 levels denoted as θ_{tc-j} for $j = 0, 1, 2, \dots, 9$.

2.3.2. PWMER Sensors

(1) PWMER sensor: The model is RS-ECTH-N01, and the power supply voltage is 4.5~30 VDC. It uses the principle of resistance method [34] to measure the electrical conductivity of soil EC_a , with a conductivity accuracy of $\pm 5\%$ $\mu\text{S}/\text{cm}$ and a measurement range of 0~5000 $\mu\text{S}/\text{cm}$.

(2) Salt content design: According to the measurement range of the PWMER sensor, the design salt content adopts NaCl (purity 99.9%), and its addition amount (g/kg) is 0, 1.5, 3.0, 4.5, 6.0, and 7.5, a total of 6 levels, recorded as $M_{p-i}, i = 0, 1, 2, \dots, 11$.

(3) Moisture content design: In accordance with conditions favorable for crop growth, the correlation between soil moisture content and field capacity is considered. The design moisture content ranges from 10% to 70% of the field capacity of deionized water, with the soil moisture content conducive to the growth of most crops falling between 40% and 70% of the field capacity. Following the principle of 'sparse first, then dense', the moisture content is set at 10, 20, 30, 40, 45, 50, 55, 60, 65, and 70, totaling 10 levels denoted as θ_{pc-j} for $j = 0, 1, 2, \dots, 9$.

2.3.3. Soil Sample Settings

Soil samples with varying gradients of water content and salt content were prepared, with each group consisting of 3 replicates. Each group involved weighing 1.5 kg of sieved soil samples and placing them into a PVC cylindrical container (16.0 cm in diameter, 14.5 cm in height). Deionized water and the specified salt were mixed in pairs according to the soil cultivation scheme until the salt was fully dissolved. Subsequently, a watering can was used to uniformly distribute the salt solution in the soil sample through stirring, ensuring even distribution of water and salt within the container [35,36]. The soil sample depth used in the test was 15 cm, which can be considered consistent with the soil moisture content post thorough mixing, thereby eliminating spatial variations in soil moisture [37]. The prepared soil samples were then subjected to testing in an environment maintained at 25 °C.

2.3.4. Measurement Method

(1) Conductivity meter method for sampling: Utilizing the BANTE520 model, soil samples are collected from three random positions within the soil. These samples are then placed on filter paper to air dry naturally, after which 10 g of each sample is extracted. Following the 1:5 soil solution conductivity measurement method, the soil sample solution is allowed to stand for 8 h and subsequently measured using a conductivity meter [38]. The resulting mean value is denoted as $EC_{wi,j}$, where i corresponds to EC_t and j corresponds to EC_p .

(2) TDR method sample: The moisture content $\theta_{tc}(\theta_c)$ and conductivity value of the soil sample are measured at 3 positions in the soil sample and the $EC_t(EC_a)$ of the soil sample. The relationship between EC_t , M_t , and θ_{tc} is recorded as $EC_{t_{ij}}$, where i is M_t , $i = 0,1,2,\dots,11$, j is θ_{tc} , and $j = 0,1,2,\dots,9$.

(3) TDR method sample: The moisture content $\theta_{pc}(\theta_c)$ and conductivity value of the soil sample are measured at 3 positions in the soil sample and the $EC_p(EC_a)$ of the soil sample. The relationship between EC_p , M_p , and θ_{pc} is recorded as $EC_{p_{ij}}$, where i is the M_p , $i=0,1,2,\dots,11$, j is θ_{pc} , and $j = 0,1,2,\dots,9$.

3. Results

3.1. TDR Sensor Verification Results

(1) Model Analysis

The soil conductivity measured by the TDR sensor is denoted as EC_t , which is associated with the water content θ_{tc} , as well as the soil solution conductivity measured by the conductivity meter EC_w , ρ_a , ρ_w , and b , along with the verification coefficient R_t^2 obtained from Equation (7). The average value $\bar{b}$ of the initial salt content $\bar{b}$ is obtained, the relative error R_e is calculated, and the corresponding calculation parameters are presented in Table 2.

Table 2. The calculation parameters of TDR sensor test.

Parameter	$\rho_a/\text{cm}\cdot\text{mS}^{-1}$	$\rho_w/\text{cm}\cdot\text{mS}^{-1}$	$b/\text{g}\cdot\text{kg}^{-1}$	$\bar{b}/\text{g}\cdot\text{kg}^{-1}$	$R_e/\%$	R_t^2	$ \bar{R}_c /\text{g}\cdot\text{kg}^{-1}$
θ_{tc_0}	−3.35	0.29	1.83	1.91	−3.97	0.85	0.33
θ_{tc_1}	3.20	0.05	1.84		−3.45	0.91	0.41
θ_{tc_2}	3.78	0.04	1.91		0.34	0.95	0.35
θ_{tc_3}	4.78	0.02	1.93		1.02	0.97	0.35
θ_{tc_4}	3.00	0.02	2.00		4.71	0.96	0.51
θ_{tc_5}	3.97	0.01	1.87		−2.00	0.97	0.24
θ_{tc_6}	3.42	0.01	1.87		−2.04	0.98	0.14
θ_{tc_7}	3.10	0.01	1.98		3.61	0.99	0.16
θ_{tc_8}	2.99	0.00	1.89		−1.11	0.97	0.16
θ_{tc_9}	2.93	0.00	1.96		2.89	0.98	0.21

As shown in Table 2, the TDR sensor measures $b > 0$, indicating the presence of initial salt content in the soil sample. The average value of b is $\bar{b} = 1.91$ g/kg, with a range of 1.83~2.00 g/kg. The relative error $|R_e| \leq 4.71\%$ is small, indicating a low level of error. Additionally, $R_t^2 \geq 0.85$, demonstrating a high level of prediction accuracy. The average error $|\bar{R}_c| \leq 0.51$ g/kg is small, further confirming the ability of the TDR sensor to accurately measure the salt content of the soil SSC using the proposed ECWS method.

Moreover, the variation in ρ_a remains relatively consistent due to the consideration of the coupling relationship among EC_t , θ_{tc} , EC_w , and SSC during the verification process using TDR sensors. This results in a stabilized trend in SSC measurements. All parameters $|\rho_w|$ exhibit a gradual decline, attributed to the coupling relationship between M_c , EC_w , and θ_{tc} when measured with a TDR sensor. Specifically, under constant M_c conditions, EC_w decreases as θ_{tc} increases. The rate of decrease in EC_w is slower than the rate of increase in θ_{tc} , leading to a gradual decrease in $|\rho_w|$ as θ_{tc} rises.

(2) Verification of results

By utilizing SSC_R as the independent variable (x-axis) and SSC_t as the dependent variable (y-axis), a linear fitting analysis is conducted to verify the correlation between SSC_R and SSC_P . The verification outcomes are visually presented in Figure 1.

Figure 1 displays the linear fitting analysis results, showing a regression coefficient $R^2 \geq 0.96$, indicating a significant relationship between SSC_R and SSC_P . This underscores the high simulation accuracy of the ECWS model for soil salinity prediction. Moreover, the coefficients of the primary terms approaching 1 suggest a strong positive correlation between SSC_R and SSC_P . Notably, when $j = 0,1$, the error band fluctuates within a certain

range due to the impact of soil moisture content WS. Specifically, the TDR sensor measurements exhibit fluctuations under low WS conditions, leading to an increase in prediction errors within the ECWS model.

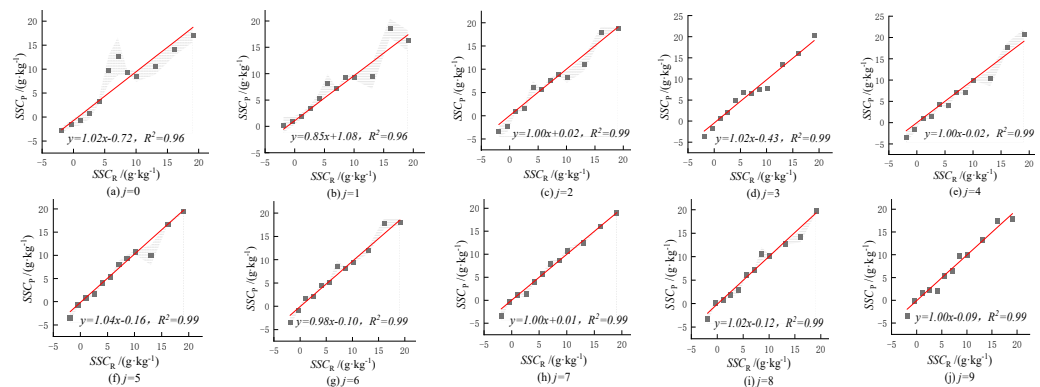


Figure 1. Linear verification of measured value SSC_R and predicted value SSC_P of TDR sensor. Note: Shaded areas are confidence intervals.

3.2. PWMER Sensor NaCl Verification Results

(1) Model Analysis

The soil conductivity measured by the PWMER sensor is denoted as EC_p , which is associated with the water content θ_{pc} , as well as the soil solution conductivity measured by the conductivity meter EC_w , ρ_a , ρ_w , and b , along with the verification coefficient R_p^2 obtained from Equation (7). The average value $\bar{b}$ of the initial salt content $\bar{b}$ is obtained, the relative error R_e is calculated, and the corresponding calculation parameters are presented in Table 3.

Table 3. The calculation parameters of PWMER sensor test.

Parameter	$\rho_a/cm \cdot mS^{-1}$	$\rho_w/cm \cdot mS^{-1}$	$b/g \cdot kg^{-1}$	$\bar{b}/g \cdot kg^{-1}$	$R_e/\%$	R_t^2	$ \bar{R}_c /g \cdot kg^{-1}$
θ_{pc_0}	6.97	0.04	1.80	1.89	−4.78	0.92	0.04
θ_{pc_1}	3.42	0.05	1.82		−3.63	0.88	0.33
θ_{pc_2}	2.00	0.02	1.85		−1.95	0.86	0.44
θ_{pc_3}	8.10	−0.04	1.87		−0.86	0.88	0.26
θ_{pc_4}	5.73	−0.03	1.90		0.74	0.96	0.12
θ_{pc_5}	3.62	−0.01	1.91		1.26	0.94	0.22
θ_{pc_6}	0.13	0.03	1.90		0.53	0.89	0.43
θ_{pc_7}	4.55	−0.04	1.94		2.78	0.90	0.37
θ_{pc_8}	1.15	0.02	1.98		4.63	0.95	0.29
θ_{pc_9}	3.02	−0.02	1.89		0.34	0.95	0.21

As shown in Table 3, the PWMER sensor measures $b > 0$, indicating the presence of initial salt content in the soil sample. The average value of b is $\bar{b} = 1.89$ g/kg, with a range of 1.80~1.98 g/kg. The relative error $|R_e| \leq 4.78\%$ is small, indicating a low level of error. Additionally, $R_p^2 \geq 0.86$, demonstrating a high level of prediction accuracy. The average error $|\bar{R}_c| \leq 0.44$ g/kg is small, further confirming the ability of the PWMER sensor to accurately measure the salt content of the soil SSC using the proposed ECWS method.

In addition, the ρ_a and $|\rho_w|$ of the fitting treatment showed a decreasing trend, because when the M_p is constant, the EC_p gradually increases with the increase in θ_{pc} , while the rate at which the EC_w decreases with θ_{pc} is less than the growth rate of moisture content. Therefore, when θ_{tc} increases, ρ_a and $|\rho_w|$ gradually decrease.

(2) Verification of results

By utilizing SSC_R as the independent variable (x-axis) and SSC_p as the dependent variable (y-axis), a linear fitting analysis is conducted to verify the correlation between SSC_R and SSC_p . The verification outcomes are visually presented in Figure 2.

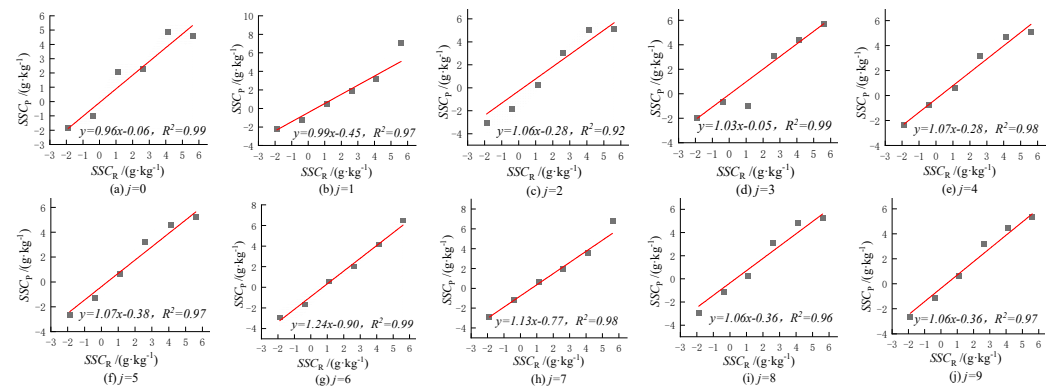


Figure 2. Linear verification of measured value SSC_R and predicted value SSC_p of PWMER sensor. Note: Shaded areas are confidence intervals.

Figure 2 illustrates a linear fit analysis, revealing a regression coefficient $R^2 \geq 0.92$, signifying a significant relationship between SSC_R and SSC_p . This underscores the superior simulation accuracy of the ECWS model in predicting soil salinity. Moreover, the primary term coefficients closely approximating 1 suggest a strong positive correlation between SSC_R and SSC_p . Similarly to the TDR sensor testing, this correlation is influenced by soil moisture content (WS). In particular, under low moisture content conditions ($j = 0, 1, 2, 3$), the error band exhibits substantial variability.

3.3. PWMER Sensor KCl and K_2SO_4 Verification Results

To explore the impact of different ions on the ECWS model, experimental studies were conducted using KCl and K_2SO_4 . The soil samples used in the testing were sourced from sandy soil at the apple orchard of the 10th regiment in Alar, Xinjiang. The PWMER sensor was employed to measure the soil conductivity EC_p and moisture content θ_{pc} , while the soil solution conductivity EC_w was determined using a conductivity meter. KCl and K_2SO_4 were added at levels of 0, 3, 6, and 9 g/kg for testing.

Given the utilization of the ECWS model by the PWMER sensor in scenarios of low moisture content during validation tests, where significant discrepancies between predicted and measured salt content values occur, a gradient design approach for the water content θ_{pc} was implemented. This design involved varying θ_{pc} at 40%, 50%, 60%, and 70% of the field's water holding capacity, denoted as θ_{pc} , $j = 0, 1, 2, 3$. The soil sample preparation followed the methodology established in the verification test to maintain consistency in the experimental procedures.

(1) Model Analysis

The ECWS model formula was utilized to derive ρ_a , ρ_w , and b and validate the coefficient R_p^2 . Then, we calculated the average initial salt content $\bar{b}$ and relative error R_e . The absolute error $|\bar{R}_c|$ between the measured average salt content $\overline{SSC}_R$ and predicted average salt content $\overline{SSC}_p$ was then computed. The outcomes are presented in Table 4.

From Table 4, it is observed that the base salt content $\bar{b}$ 1.84 g/kg and $|R_e| \leq 1.55\%$ were achieved when K_2SO_4 was included in the experiment. The relative error $|\bar{R}_c| \leq 0.20$ g/kg between the measured and predicted average salt content values. Furthermore, the base salt content $\bar{b} = 1.92$ g/kg, and $|R_e| \leq 2.79\%$ were obtained when KCl was added to the study. The relative error $|\bar{R}_c| \leq 0.37$ g/kg between the measured and predicted mean salinity values. The R_p^2 of both salts from the ECWS model was not less than 0.9, indicating a high level of fitting accuracy.

Table 4. Verification results of K_2SO_4 and KCl.

Salt	K_2SO_4				KCl			
Parameter	θ_{pc_0}	θ_{pc_1}	θ_{pc_2}	θ_{pc_3}	θ_{pc_0}	θ_{pc_1}	θ_{pc_2}	θ_{pc_3}
ρ_a ($cm \cdot mS^{-1}$)	10.79	7.00	4.03	1.09	8.25	7.75	3.26	0.30
ρ_w ($cm \cdot mS^{-1}$)	0.05	−0.01	0.02	0.04	0.00	−0.07	−0.02	0.04
b ($g \cdot kg^{-1}$)	1.85	1.81	1.86	1.83	1.89	1.97	1.91	1.89
$\bar{b}$ ($g \cdot kg^{-1}$)		1.84				1.92		
R_e (%)	0.65	−1.55	1.18	−0.44	−1.32	2.79	−0.26	−1.32
R_p^2	0.97	0.99	0.98	0.99	0.98	0.93	0.97	0.97
$ \bar{R}_c $ ($g \cdot kg^{-1}$)	0.15	0.01	0.18	0.20	0.07	0.37	0.25	0.28

From Table 4, it is evident that the base salinity and salinity prediction resulting from the addition of K_2SO_4 are lower than those obtained by adding KCl. This difference can be attributed to the higher adsorption of K^+ and SO_4^{2-} ions from K_2SO_4 compared to K^+ and Cl^- ions from the soil solution, leading to a reduction in electrical conductivity due to the adsorption effect [39]. However, since Cl^- is the most reactive anion in the soil, when equal amounts of KCl and K_2SO_4 are added, the soil's ionic content is higher with the addition of KCl, resulting in higher soil conductivity and measured base salt content.

As shown in Tables 3 and 4, the base salinity $\bar{b}$ 1.89 g/kg obtained by adding NaCl is lower than the value obtained by adding KCl when the same amount of KCl and NaCl is used. This suggests that Na^+ contributes less to soil salinity compared to K^+ from KCl. Therefore, when utilizing the ECWS salinity measurement model, Cl^- predominates over SO_4^{2-} , and K^+ dominates over Na^+ among the anions and cations influencing salinity.

(2) Verification of results

By utilizing SSC_R as the independent variable (x-axis) and SSC_t as the dependent variable (y-axis), a linear fitting analysis is conducted to verify the correlation between SSC_R and SSC_p . The verification outcomes are visually presented in Figure 3.

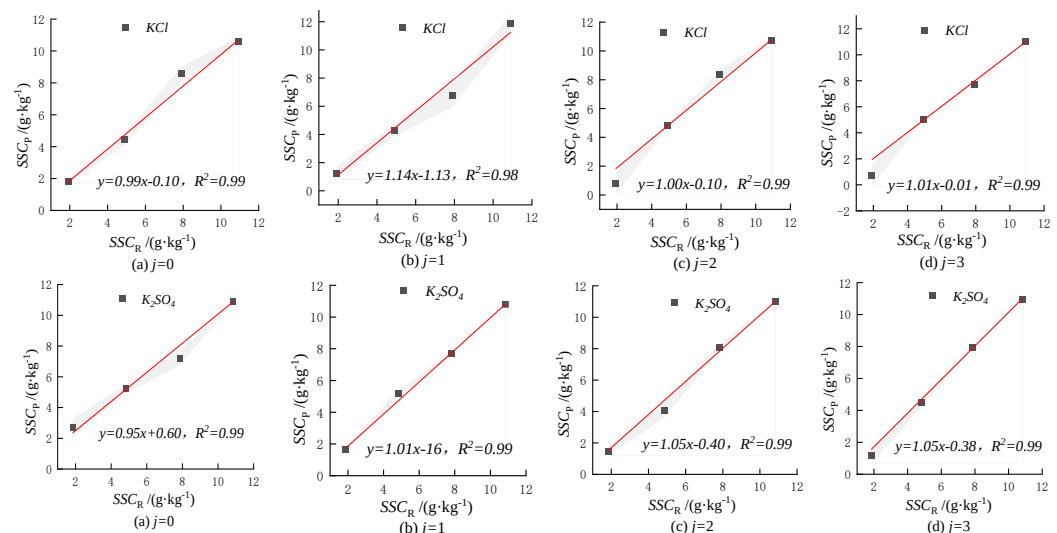


Figure 3. Verification results of PWMER sensor KCl and K_2SO_4 . Note: Shaded areas are confidence intervals.

As depicted in Figure 3, the regression coefficient of the linear fit for K_2SO_4 and KCl was $R^2 \geq 0.9$, indicating a strong correlation between SSC_R and SSC_p . The coefficients of the primary terms for both salinities are closely aligned to one another. Since the water content design was examined starting from 40% of the field capacity, the fluctuation in

the error range was minimized. Consequently, the ECWS model and method prove to be effective in accurately measuring soil salinity across various salinity levels.

4. Discussion

Soil salinity is a major factor affecting soil fertility and crop yield [40,41], and one of the most important indicators for assessing the degree of soil salinity [42]. The measurement of soil salinity is very important for the improvement of saline soils, so through the combination of soil bulk conductivity, soil solution conductivity, and volumetric water content, the ECWS model of soil salinity has been proposed, which is very important for soil salinity monitoring.

In this study, when the TDR sensor validated the ECWS model, it was shown that $|\rho_a|$ and $|\rho_w|$ gradually decreased as the water content gradually increased. The reason is that when the soil water content is small, due to the effect of annular pore space between the soil particles, the direct contact between the TDR sensor and the soil was destroyed, resulting in smaller EC_t and θ_{tc} measurements, which is consistent with the results of a previous study [33]. The literature [43] showed that EC_w decreased with the increase in water content, and the results of the present study were similar, so that $|\rho_a|$ and $|\rho_w|$ gradually decreased with the increase in θ_{tc} for a certain M_p and b , which also reflected the coupling relationship between EC_t , θ_{tc} , EC_w , and SSC.

When the PWMER sensor is validated against the ECWS model using KCl, NaCl, and K_2SO_4 , ρ_a also shows a decreasing trend with increasing water content, which is the same pattern as that of the TDR validation, while the $|\rho_w|$ pattern is not the same, suggesting that when using the ECWS model, ρ_a is less affected by the way the measurements are made than $|\rho_w|$. Meanwhile, $\bar{b}$ was 1.84 g/kg, 1.89 g/kg, and 1.92 g/kg, respectively, and the measured basic salt content gradually increased, which was due to the different adsorption capacity of soil solution for different ions, and according to the analysis of the correlation between different ions and conductivity by Zhang [44], it can be found that the correlation of Na^+ , K^+ , Cl^- , and SO_4^{2-} with the conductivity coefficient was not less than 0.98. The ionic content of K_2SO_4 was greater than that of the other two salts, and therefore the $\bar{b}$ obtained for K_2SO_4 was the largest. This also shows that the measurement of soil salinity can also be affected by the ionic species and content.

5. Conclusions

In this study, we introduce a method and model for ECWS soil salinity measurement based on electrical conductivity and moisture content. We take into account the influence of soil conductivity and moisture content on soil salinity measurement. We introduce parameters such as θ_c , the soil salinity conductivity conversion coefficient ρ_a , and soil leaching solution salinity conductivity conversion coefficient ρ_w, ρ_a and ρ_w . We also partition the total soil salinity into the salt incorporation amount and the initial soil salinity amount. Subsequently, we conduct a validation test using the TDR sensor and the PWMER sensor. The key findings are summarized as follows:

The analysis of the TDR sensor and PWMER sensor models reveals that the base salinity of the soil samples is approximately 1.9 g/kg. The relative errors have absolute values of $|R_e|$ less than 4.8%, and the R^2 values are both greater than 0.85. Hence, the ECWS model is suitable for soil salinity measurement using both TDR and PWMER sensors.

The analysis of the measured SSC_R and predicted SSC_P by both the TDR sensor and PWMER sensor revealed a strong positive correlation between SSC_R and SSC_P . The mean absolute error, $|\bar{R}_c|$, was within an acceptable range of 0.51. The error margin was influenced by the moisture content, specifically at 51 g/kg. It is essential to consider moisture content when employing this model and method for soil salinity measurement.

During the validation of the model with different salinities (K_2SO_4 , KCl, NaCl), the parameter b , obtained from various salts, was approximately 1.9 g/kg. The deviation of b obtained from different salts using the ECWS model was below 5%, indicating a high level of measurement accuracy. Hence, the ECWS model, in conjunction with the

proposed method, proves to be effective in accurately measuring soil salinity across various salinity levels.

The validation test demonstrates the viability of utilizing the ECWS model and method for salinity measurement. Considering soil bulk conductivity, solution conductivity, and water content enhances measurement accuracy. Additionally, this approach offers a reference point for monitoring temporal changes in soil salinity during the measurement process.

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