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Original Article

An Application of Soil Electrical Conductivity Measurement by Wenner Method in Paddy Field

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Abstract - *The Vietnamese Mekong Delta (VMD) is one of the agricultural production areas mostly affected by salinization. However, the majority of research topics related to soil electrical conductivity (Soil EC) used mostly soil sampling and laboratory analysis methods or imported equipment, which is costly and time-consuming. The purpose of this study is to measure soil EC using the apparent resistivity method. To compare the obtained values, the Wenner electrode system is used with distances of 5, 10, and 30 cm. The obtained results are compared with the results obtained from the Soil EC Hanna HI98331 device on wet rice farms when the soil was dried after sowing. The study found that when the electrode distance was 5 cm and the electrode depth was between 2.5 and 5 cm, the soil EC values obtained in the water environment had a strong correlation (R=0.9992, RMSE=0.0087) with those from the Hanna HI98331 device. When the electrode depth was less than 2.5 cm in the soil environment, and the electrode distance was still 5 cm, the correlation was still good (R=0.85, RMSE=0.0053). However, when the electrode distance was increased to 10 cm, the EC was averaged at a depth of 10 cm, resulting in a lower correlation (R=0.46, RMSE=0.027), and the correlation (R=0.49, RMSE=0.075) when the electrode distance was 30 cm.*

Keywords - *Soil electrical conductivity, Wenner method, Soil electrical conductivity mapping, Equipotential line, Soil salinity.*

1. Introduction

Cereal crops, particularly rice, which is vital for over 3 billion people worldwide, are predominantly produced and consumed in Asian countries. In this region, there are approximately 250 million rice farms with an average size ranging from 0.5 to 4 hectares [1]. This area is home to the majority of low-income populations in developing countries [2]. Surveying recent studies [3-81] on the application of devices and technologies in modern agriculture, specifically in-field soil electrical conductivity, the results reveal that most of the research has been conducted in arid and semi-arid regions.

The primary focus of these studies has been on crops such as corn, soybeans, and wheat, with limited research conducted on rice cultivation. Climate change has severely impacted agricultural production and food security in several countries worldwide. Therefore, sensors have been used to assess soil salinity to come up with appropriate strategies to ensure crop productivity [82]. Vietnam is a major rice exporter in the world, with the majority of wheat production concentrated in the Mekong Delta. Still, this region is vulnerable to the effects of climate change [83]. Saltwater intrusion affects not only local agricultural production but also the distribution of population, income, and expenditure in each household [84].

Most of the rice cultivation areas in the region consist of small, non-consolidated plots [85], posing difficulties in adopting high-cost modern equipment. So, monitoring and mapping the farm environment in the Mekong Delta is an essential need.

Soil EC is the ability to conduct electric currents in the soil, including currents that can move through soil particles, between soil particles and liquids, or through liquids in the soil [86]. Soil EC is a commonly used indicator for measuring soil salinity or assessing water loss in saline-affected soil.

Soil electrical conductivity can be considered as an indicator of soil salinity that is representative of soluble or slightly soluble salts (e.g., Na^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, HCO_3^-, NO_3^-, SO_4^{-2} and CO_3^{-2}) [55, 87, 88]. In addition, soil electrical conductivity is related to soil physical properties, including soil texture, cation exchange capacity, water holding capacity, and clay content [67]. So, the soil EC map can be used to monitor soil health status or to map soil salinity [87, 89]. There have been studies on electrical conductivity related to rice yield. The study of M.S.M. Amin et al. showed that rice yield is positively correlated with electrical conductivity, nitrogen, potassium, organic carbon, and pH concentrations [90].

However, conductivity mapping is used as a tool that can explain the increase or decrease in crop yield [67, 90]. In addition, these maps can be applied as an effective tool in precision agriculture [91, 92]. The correlation between soil conductivity and crop yield in the Mekong Delta requires further studies. There are many methods to measure earth resistivity. In the study of Dennis L. Corwin [55] showed that there are two methods of measuring soil conductivity in the field, including the resistivity method (Wenner array). With this method, two electrodes are used to measure the voltage difference at two points. Combining measured results with the current flowing into the earth to calculate the resistivity, that method can calculate the earth's conductivity.

The second method [67, 89, 93] is the electromagnetic induction solution, which uses a coil that emits electromagnetic radiation, combines a coil that captures the electromagnetic energy, and converts it into an electric current, and from there, the conductivity is calculated. With the method of soil resistivity, for simplicity, the conductivity in the soil occurs in 3 ways, including the conduction between soil particles and water conductivity in the soil.

The rest is due to the electrical conduction between soil particles and water. Although there are different ways that soil conductivity can be measured, the resistivity method has been shown to be highly reliable and effective in mapping soil conductivity for soil salinity management. To address the issue of high-tech equipment for conducting research in rice field environments in the Mekong Delta, this study aims to utilize direct current measuring devices for implementing physical measurements. The main objective of this study was to measure soil EC through soil resistivity using the Wenner method with an electrode spacing of 5, 10, and 30 *cm* and compare it with soil EC value measured from the Hanna HI98331 device. The mapping of soil EC has been conducted using the Surfer software, which comes with the integrated Kriging interpolation tool.

2. Materials and Methods

2.1. Study Area

The study was carried out on alluvial soil for wet rice cultivation in Thoi Lai area of 4,000 m^2 (zone A) and 14,000 m^2 (zone B) (10001'28"N, 10034'46"E WGS84) about 20 km west of Can Tho city (Fig. 1). Although it is land for rice cultivation with 3 crops/year, however, starting from the Summer – Autumn crop to the stage of tillage for the Winter-Spring crop (June to November), the land is often flooded due to rain or water season. The location of land is located inside the sewer line to prevent water under the O Mon - Xa No subproject. The climate of this area is tropical monsoon. Dry weather occurs from December to April of the following year, during which salinity intrusion often occurs. Conversely, the remaining period experiences monsoon rains, with a particular risk of flooding from upstream waters from August to November each year.

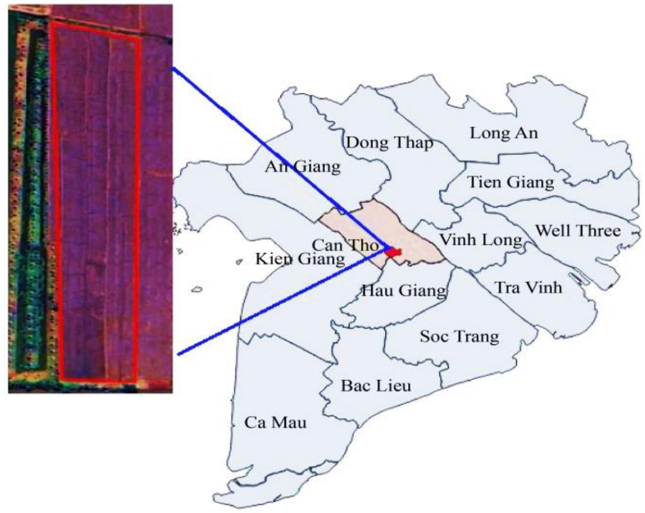

Fig. 1 Map of the study area (CanTho City in Mekong Delta, Viet Nam)

2.2. Apparent Resistivity and Wenner Method

The resistivity survey method has been applied in many fields: Investigation of lithological underground structures, estimation of depth, thickness, and properties of aquifers and aquicludes, detection of fractures and faults in crystalline rock, mapping contamination plumes, monitoring of temporal changes in subsurface electrical properties, detection of underground cavities, classification of cohesive and non-cohesive material in dikes, levees, and dams [94]. In the field of geophysics, there are many electrode configurations for measuring the earth resistance, such as Wenner, Schlumberger, Dipole-dipole, Pole-dipole, Square array, pole-pole, and Gradient [95]. According to Ohm's law, we know that with a resistor *(R)* provided with a voltage source *(V)* at both ends, a current *(I)* will appear according to the formula $I = V/R$. With the resistance method pressure, the earth can simply be viewed as resistant. Current will be fed into the homogenous half-space through the pair of electrodes C_1 and C_2, and at this time, equipotential surfaces will appear by measuring the potential difference at two points, P_1 and P_2 (Fig.2), combining the current through C_1, C_2 we can calculate the earth resistance according to Ohm's law (also known as apparent resistivity). The depth of the soil layer is used to measure resistivity, which is proportional to the electrode spacing in the Wenner configuration (*Fig.2*) [94, 96].

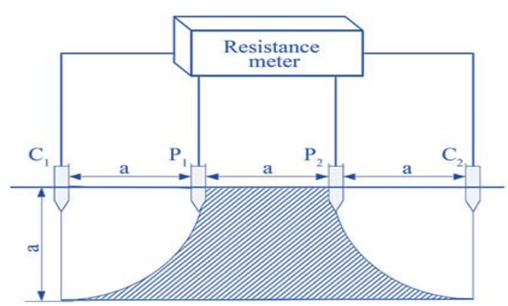

Fig. 2 The soil volume (hatched) is utilized for calculating electrical resistance in the Wenner configuration [96].

Voltage at P_1 and P_2

$$V(P_1) = \frac{I\rho}{2\pi}\left(\frac{1}{C_1P_1} - \frac{1}{P_1C_2}\right) \tag{1}$$

$$V(P_2) = \frac{I\rho}{2\pi}\left(\frac{1}{C_1P_2} - \frac{1}{P_2C_2}\right) \tag{2}$$

Voltage difference P_1 and P_2

$$\Delta V(P_1P_2) = \frac{I\rho}{2\pi}\left(\frac{1}{C_1P_1} - \frac{1}{P_1C_2} - \frac{1}{C_1P_2} + \frac{1}{P_2C_2}\right) \tag{3}$$

Resistivity of half-space

$$\rho = \frac{\Delta V(P_1P_2)}{I}.K \tag{4}$$

Where,

$$K = \frac{2\pi}{\left(\frac{1}{C_1P_1} - \frac{1}{P_1C_2} - \frac{1}{C_1P_2} + \frac{1}{P_2C_2}\right)} \tag{5}$$

In the case of a homogeneous medium, the current lines will be stable for different measurements, and then the isostatic surfaces will retain their original structure. However, when the measurement environment has a change in the resistivity of the soil layers, the current lines will no longer be kept as they were, and the structure of the equipotential lines will be distorted [95]. The significance of formula (4) lies in its ability to determine the resistivity of the environment below through measurements taken above the ground. Nonetheless, given the non-uniform nature of the geological environment, as illustrated in Figure 3, employing formula (4) enables the calculation of a value denoted as *ρ (Ω.m),* commonly known as apparent resistivity. In studies on earth resistivity [61], Wenner showed that with the distance of electrodes C_1, P_1, P_2, and C_2 from each other, a distance *a (m)* and electrode depth *b (m)*, in the condition $b<a$ can calculate the resistivity *ρ (Ω.m)* according to the formula:

$$\rho = 2\pi aR \tag{6}$$

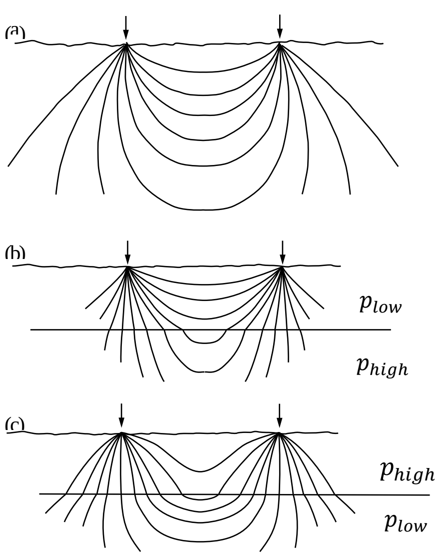

Fig. 3 DC model (a) soil has uniform resistance; (b) the soil resistance of the upper layer is higher than the lower layer; and (c) the soil resistance of the upper layer is lower than the lower layer [95].

Where *R (Ω)* is the earth's resistance between two equipotential surfaces at two measured points, P_1 and P_2, which can be seen as the earth's cylindrical resistance with length *a* and radius *2a*.
Electrical conductivity *σ (S/m)* is calculated:

$$\sigma = 1/\rho = 1/2\pi aR \tag{7}$$

2.3. Data Acquisition System

The system utilizes a specialized DC voltage measurement device with two channels for voltage measurement and one channel for current measurement using a series-connected method with a 100-ohm resistor across the Ground (GND) terminal.

The industrial touch screen (HMI) supports the Modbus communication protocol for connection to the voltage measurement device. The touchscreen has a memory card slot for data storage, and a 12V DC power supply powers the system. The system is installed on a universal backpack and can integrate a Global Positioning System (GPS) when needed.

The configuration of electrodes for measuring electrical conductivity is established *(*Fig.4*)*, where electrodes 2, 3, 4, and 5 are configured at a distance of 10 *cm*, and electrodes 1, 2, 5, and 6 are configured at a distance of 30 *cm*.

2.4. Soil Sampling, Analysis and Mapping

The electrodes using stainless steel are rod electrodes with a diameter of 5 *mm*, each electrode length is 30 *cm*, and the electrode spacing is 5 *cm*.; The electrode depth was compared in aqueous medium with smaller and larger electrode depth of half the distance. Salt is quantified in small bags of 1 g using the Ohaus bench scale (USA), error ±10mg; salt was mixed in 60 liters of water, and the measured results between the 5 *cm* electrode system and the Hanna HI98331 device on the muddy soil used for rice cultivation, the independence between the measurements were compared with all the above depths.

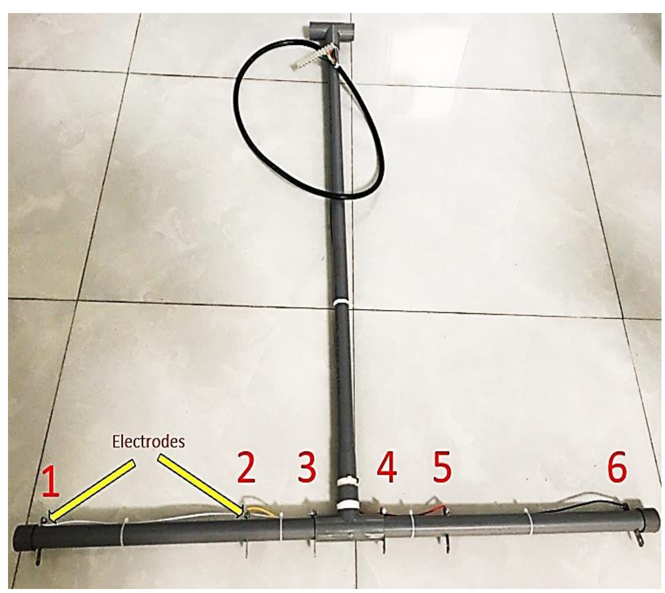

Fig. 4 Electrode for measurement soil EC in paddy field

Calibration in a water environment: The depth of the Wenner electrodes in water is fixed, and the measured values of both methods are recorded in a table. Subsequently, the water is agitated for approximately 2 minutes to ensure the added salt is completely dissolved, and the measurement values are recorded. This process is repeated after each measurement. The same procedure is carried out after increasing the depth of the electrodes in water to compare the results across measurements.In zone A, Hanna measurement equipment and Wenner electrode configurations are at 5, 10, and 30 *cm* electrode spacings, each with a constant electrode length.

In zone B, Wenner electrode configurations at 10 and 30 *cm* were utilized to measure EC at two-time points: the first measurement was carried out after land preparation and before sowing the Summer-Autumn crop. In contrast, the second measurement was conducted before sowing the Winter-Spring crop (EC-B1). The fields had been submerged in floodwater for approximately 3 months before sowing the Winter-Spring crop (EC-B2), resulting in softer soil compared to the previous period. In these two sampling rounds, a total of about 800 data points were collected for both electrode configurations.

2.5. Interpolation Method

Kriging is a spatial interpolation method that considers both the distance and variability between known data points to predict values at points in unknown areas [17].

Z_i is the soil EC of the interpolated i

$$Z_{P(x,y)} = \sum_{i=1}^{n} \lambda_i Z_i \tag{8}$$

Where λ_i is calculated from the equation:

$$A^{-1}b = \binom{\lambda}{\theta} \tag{9}$$

Where θ is the Lagrange coefficient

$$A = \begin{pmatrix} A_{1,1} & A_{1,2} & \dots & A_{1,n} & 1 \\ A_{2,1} & A_{2,2} & \dots & A_{2,n} & 1 \\ \dots & \dots & \dots & \dots & \dots \\ A_{n,1} & A_{n,2} & \dots & A_{n,n} & 1 \\ 1 & 1 & \dots & 1 & 1 \end{pmatrix} \tag{10}$$

$$b^T = \begin{pmatrix} A_{P,1} & A_{P,2} & \dots & A_{P,n} & 1 \end{pmatrix} \tag{11}$$

where $A_{i,j}$ are the semi-variance values calculated from the exponential half-variance function model

$$A(S) = A_0 + A_1\left(1 - e^{-\frac{S}{a}}\right) \tag{12}$$

$$S_{i,j} = \sqrt{\left(x_i - x_j\right)^2 + \left(y_i - y_j\right)^2} \tag{13}$$

Where A_0, A_1, a are the parameters to be determined

Data correlation analysis uses EXCEL software to plot graphs and calculate parameters. Surfer 19.2 software is used to draw Kriging interpolation maps with recalibrated GPS coordinates to observe the data.

3. Results and Discussion

3.1. Measurement in the Water Environment

In the condition of a homogenous environment, water and electrode depth of 2.5 *cm* will give the best correlation between the soil EC value obtained from the Wenner electrode system and HI98331 device with R^2=0.9991, RMSE ≈ 0 *(see Fig. 5).*

In *Fig. 5*, when the depth is increased to 2.8 *cm,* the result is correlated with $y = 1.2223x + 0.0124$; R^2=0.09984, however, in this case the difference between the two devices increases with increasing salt.

3.2. Measurement in Soil Environment

3.2.1. In zone A

Soil EC results *σ* (*mS/cm*) were obtained on soil environment at all 3 measurements with 100 data points for depth of 5 and 10 *cm* and 50 points for depth of 30 *cm*. Experiments were performed independently when comparing two-device results. The soil EC measurement data were taken on rice land, which became muddy after half a year of wetlands due to flooding from the Mekong River.

The Hanna device achieved the value of soil conductivity after measurements in the range of 0.08 - 0.79 *mS/cm*. The results obtained from the Wenner method range from 0.1 to 1.2 *mS/cm* (*Table 1*). After the soil is submerged for a long time, the soil EC value tends to increase with the depth of the soil. The HI98331 device, with a length of 114 *mm*, is unable to measure soil EC at depths greater than this. The obtained values cannot represent the EC index at a depth of 30 *cm* *(Fig.6).* The Wenner electrode configuration at a distance of 5 *cm* shows a strong correlation with results obtained from the Hanna measuring device in the soil environment prior to sowing the Winter-Spring crop.

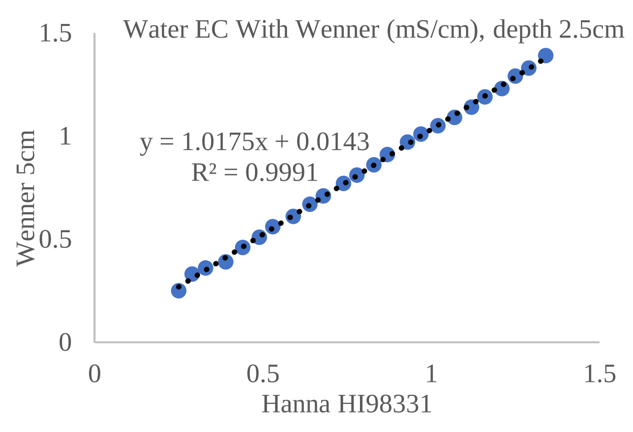

Fig. 5 Water EC correlation results from Hanna HI98331 instrument and Wenner method

3.2.2. In zone B

After conducting soil EC measurements in this area, the results show a decreasing trend in soil EC at a depth of 0-10 cm over the prolonged period of soil submersion. Soil EC at a 0-30 cm depth also experiences a reduction, but the values do not vary significantly compared to the 0-10 cm depth (Fig.6).

3.3. Soil EC Mapping

Observational results from the Kriging interpolation map show that soil EC has a lower distribution of soil EC than the layer below by area. High-value conductivity at the top and bottom of the plot was recorded at all measurements at 10 and 30 cm (Fig.7).The change in soil EC is insignificant in the 0-5 cm surface layer, and substantial variations begin as the survey extends to greater depths (Fig.8).

3.4. Discussion

Using the Wenner method to indirectly measure soil electrical conductivity through apparent resistivity readings with a DC resistivity meter has yielded the best results, especially in aquatic environments, with an $R^2 \approx 0.9991$ and RMSE ≈ 0. Similarly, this index has shown remarkable performance in soil environments with an $R^2 \approx 0.73$ at an electrode spacing of 5 *cm*, decreasing as the electrode distance increases to 10 and 30 *cm*.

After an extended period of rice field inundation, the electrical conductivity index of the 0–5 *cm* soil layer in the research area exhibited less variation than deeper soil layers. Variations in soil EC were observed at two points before sowing the Summer-Autumn and Winter-Spring crops at a 0–10 cm depth.

There is currently no research establishing a connection between the water source in the study area and salinity contamination. However, the electrical conductivity of water during periods of high flood conditions needs further investigation to determine if it is a contributing factor to these variations. The difference in soil EC at a depth of 0–30 *cm* is more pronounced than at smaller agricultural distances, suggesting that sampling experiments based on soil EC variations on the map could provide more comprehensive results.

The use of DC power induces polarization, and the corrosion of electrodes over extended periods or under saline conditions needs addressing. While the results are promising for continued use in subsequent research, efforts to improve the manual sampling method are required to enhance efficiency and speed.

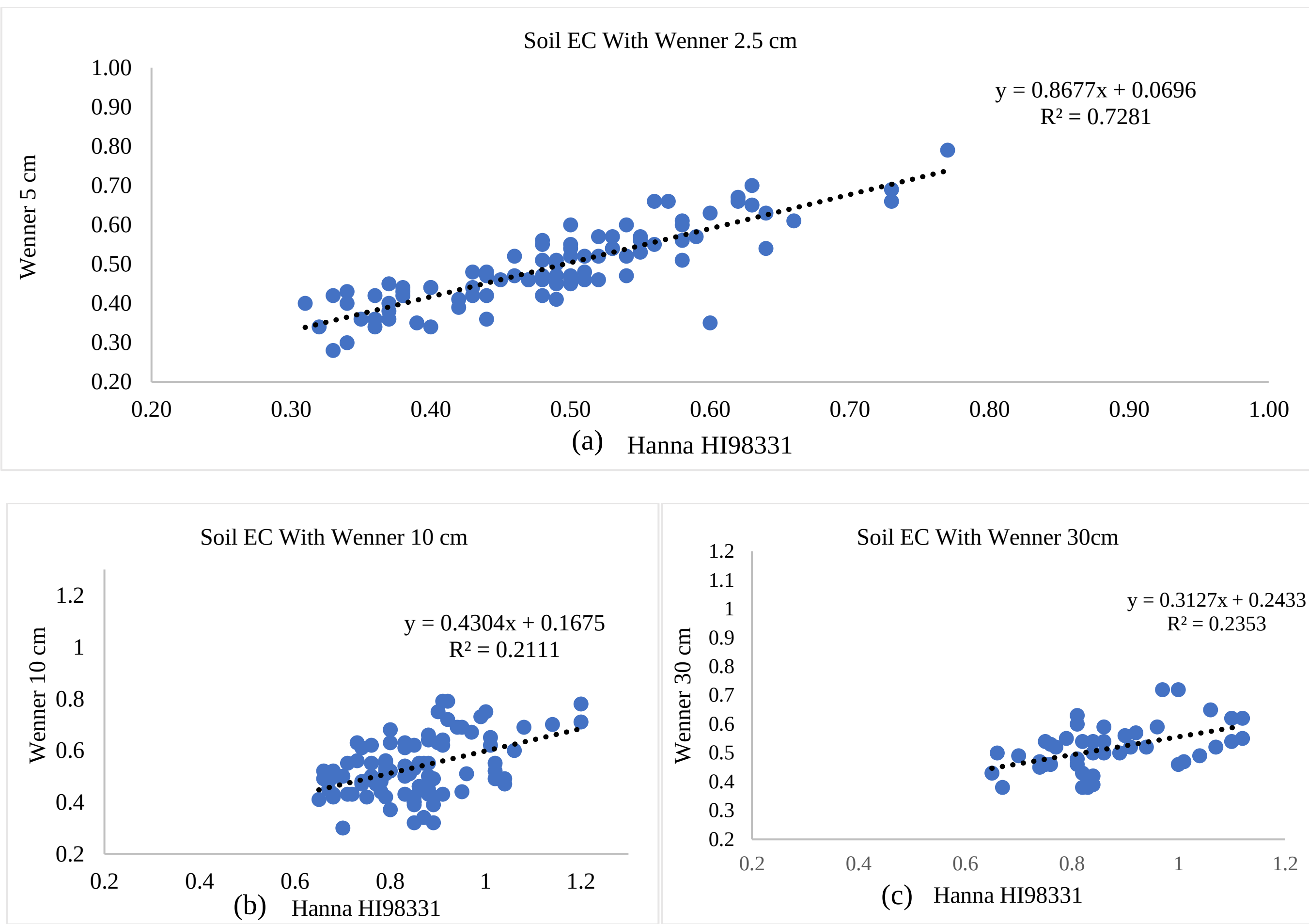

Fig. 6 Soil EC correlation results from Hanna HI98331 device and Wenner method with electrode distance (a) 5 cm, (b) 10 cm, and (c) 30 cm.

Table 1. The results of Soil EC measurement by the Wenner method and Hanna device

	Depth 5 *cm*		**Depth 10 *cm***		**Depth 30 *cm***	
	Wenner	HI98331	Wenner	HI98331	Wenner	HI98331
Max	0,77	0,79	1,2	0,79	1,12	0,72
Min	0,31	0,28	0,65	0,3	0,65	0,38
Means	0,49	0,49	0,85	0,53	0,87	0,52
Std. Deviation	0,1	0,10	0,12	0,11	0,13	0,08

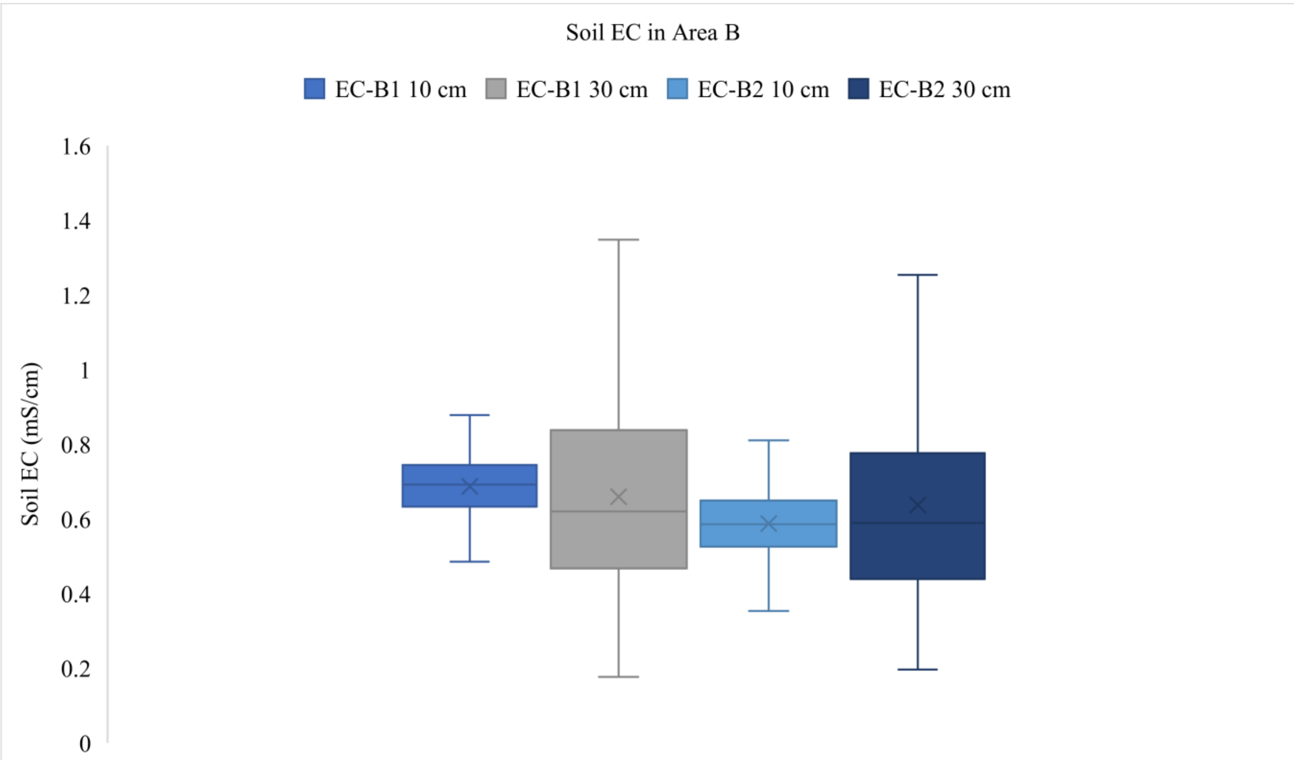

Fig. 7 Results of soil EC collection in zone B

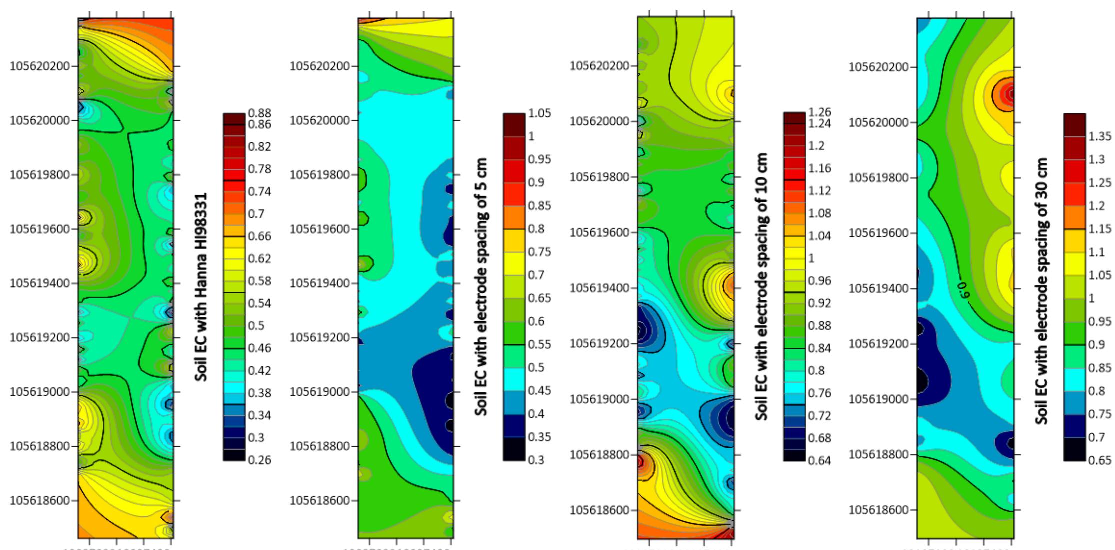

Fig. 8 Soil EC interpolation map measured with Hanna HI98331 device and Wenner method with electrode distance 5, 10, and 30 cm.

4. Conclusion

Impressive outcomes were achieved in both soil and water environments, with the results obtained using the Wenner electrode system combined with a DC power source. This outcome suggests that farmers in developing countries can utilize this tool to assess the soil and water salinity conditions in their fields. However, the study was limited to a small area, and there is currently no regional evidence regarding historical soil salinity levels. Therefore, expanding the research on a larger scale and incorporating coastal areas prone to salinity contamination is essential to obtain higher-resolution soil EC results.

Measuring the electrical conductivity of the saturated paste extract using a laboratory-scale method provides the highest accuracy. However, generating a sufficiently large test sample mass for comparison with the large-configured Wenner methods requires significant effort and cost, making it impractical for this study. Therefore, this index should be considered merely as a tool to assess the variability of soil EC based on consistent measurements. Future research in flooded rice field conditions, such as the Mekong Delta, can build upon these findings.

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