

Evaluation of Correlation and Regression Relationships Between Soil Solution Electrical Conductivity and Major Ion Concentrations

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Abstract

Since the electrical conductivity (EC) of soil solutions directly reflects the total concentration of dissolved ions, it is considered one of the most reliable and widely used indicators for assessing the salt content in the soil. EC parameters, acting as a comprehensive indicator of the content of soluble salts, are closely related to many physicochemical properties of the soil, including food mobility, plant water supply, soil fertility, and long-term productivity of agricultural systems. In this context, identifying ions that directly influence fluctuations in electrical conductivity is fundamental to understanding salinization dynamics, evaluating the effectiveness of Reclamation measures, and developing sustainable soil management strategies. The presented research work was carried out with the aim of studying the degree of influence of the main dissolved cations (Na^+ , Ca^{2+} , Mg^{2+} , K^+) and anions (Cl^- , SO_4^{2-} , HCO_3^-) on the electrical conductivity of the soil solution. Pearson analysis was used to determine the intensity of the correlation between EC and individual ions. To determine the relative weight and significance of each variable, the multidimensional linear regression method and standard regression coefficients were used. The combined use of these statistical methods allowed an in-depth analysis of the Ionic factors that control EC changes and the correct separation of large and small factors that affect soil salinization. Statistical analysis showed that the elements with the strongest positive correlation with electrical conductivity are sodium (Na^+) and chloride (Cl^-). This situation also confirms that these two ions play a dominant role in the accumulation of soluble salts in the studied soils. Although significant positive correlations were also recorded with calcium (Ca^{2+}), magnesium (Mg^{2+}) and sulfate (SO_4^{2-}) ions, their final effect on EC was poor compared to sodium and chloride. Conversely, potassium (K^+) and bicarbonate (HCO_3^-) ions showed both low standard regression coefficients and relatively weak correlations. This result shows that in modern research conditions, the ratio of these ions in EC oscillations is very limited. In general, the results obtained more clearly reveal the mechanism of influence of the ionic composition of the soil solution on its electrical conductivity and prove that the main driving forces that determine salinity in the studied medium are sodium and chloride. The study also confirms the effectiveness of multidimensional statistical methods when interpreting the chemical properties of soils and looking for the most informative indicators of salinization. In conclusion, we can say that this study provides an important scientific framework for improving the assessment of salinity, developing Reclamation methods and managing irrigation, and supporting the sustainable use of saline arable land. In addition, the presented analytical base can be used in future studies as a useful tool for monitoring soil quality and predicting the risks of salinization in various environmental and agricultural conditions.

Keywords: soil salinity, Pearson correlation, multiple linear regression, standardized regression coefficient, soil reclamation, sustainable land management

1. Introduction

Soil is one of the most complex natural systems in which physical, chemical and biological components interact continuously, creating a dynamic and heterogeneous environment (Weil, Brady & Weil, 2017). As the main life-supporting environment for soil plants, soil provides them with water and essential mineral nutrients necessary for plant growth and development. In addition to its agricultural function, it also regulates numerous ecosystem processes, promoting food circulation while maintaining biological activity and environmental stability.

Among the various components of the soil, the soil solution occupies a central place, since it most often serves as the medium through which physico-chemical, biochemical, and biological reactions take place. The soil solution, which acts as a link between the solid soil and the plant roots, controls the transport, transformation, and availability of solutes. Therefore, its composition and physicochemical properties largely determine the mobility of nutrients, their assimilation by plants, and the overall fertility of the soil. Thus, differences in the chemical composition of the soil solution provide valuable information about the state of the soil and its environmental activity (Abrol et al., 1988).

A careful assessment of the properties of the soil solution is necessary to determine soil fertility, increase irrigation efficiency, and apply sustainable soil management methods. In modern agricultural conditions, which are characterized by intensive agriculture, increased food demand, and climate uncertainty, this importance has increased significantly. As a result, the study of the chemical composition of soil Solutions has become a key component of soil quality monitoring and environmental assessment programs around the world (Rengasamy, 2010).

One of the most serious environmental threats facing arable land in modern times is the constant increase in the level of salinization. The negative effects of climate change, limited access to freshwater resources, and the expansion of irrigated agricultural areas have further accelerated salt accumulation in many regions (Corwin, 2021). The problem in question is especially acute in arid and semi-arid regions, where the concentration of soluble salts in the soil layer increases against the background of strong evaporation and insufficient rainfall (FAO, 2021). The systematic accumulation of salt over time changes both the physical structure and the chemical composition of the soil. In this case, the strength of the aggregate decreases, the integrity and permeability of the pores decrease, and, as a result, the water-air balance in the soil deteriorates. Such structural changes make it difficult for the roots to absorb water, worsen the absorption of nutrients and, as a result, lead to a decrease in crop yield. In the long term, continuous salinization aggravates soil degradation, has a direct impact on the sustainability of agricultural ecosystems and reduces the long-term productivity potential of arable land to zero. In many irrigated regions, the poor condition of drainage networks and improperly selected irrigation methods stimulate the processes of secondary salinization and mineralization of the soil. This situation creates additional barriers to sustainable land management and significantly increases the risk of non-renewable degradation. Among the various indicators used to assess the level of salinization, the electrical conductivity of the soil solution is still considered one of the most informative and practical parameters (Corwin & Lesch, 2005). Since the EC indicator directly reflects the total concentration of dissolved ions, it allows you to quickly determine the degree of salinization of the soil. Therefore, it is regularly used in agriculture, irrigation planning, and environmental monitoring. However, although high EC values indicate a high total salt concentration, this measurement alone does not allow determining the degree of exposure to individual ions that determine electrical conductivity (Hillel, 2003). The ratio of each ion to its electrical conductivity; the ionic charge depends on a number of physicochemical factors, such as the hydration radius, electrical conductivity, and transport properties in the soil solution (Tan, 2011). Therefore, the effect of ions on the measured EC value cannot be estimated as a single unit. In this context, the assessment based solely on electrical conductivity, without considering the ionic composition, can be aimed at facilitating the interpretation of salting processes. To obtain more complete and accurate results, EC measurements should be combined with quantitative analysis of the main dissolved ions in the medium. It also allows for a more objective characterization of geochemical processes in the soil. In general, the chemical composition of the soil

solution is dominated by sodium (Na^+), calcium (Ca^{2+}), magnesium (Mg^{2+}) and potassium (K^+) cations. Chlorides (Cl^-), sulfate (SO_4^{2-}), and bicarbonate (HCO_3^-) ions are the main anions (Rhoades et al., 1999). The concentration of these ions, the equilibrium mechanisms, and the interaction between them largely determine the severity and type of disinfection, as well as the dynamics of the development of these processes (Sparks, 2019). The interaction of these ions not only controls the chemical balance of the soil but also plays a leading role in the formation of bonds between plants and soil (Essington, 2015). Disinfection of the soil by deactivation is a key factor in the formation of the soil-plant environment.

Increased concentrations of sodium and chlorides are usually associated with a predominance of neutral or chloride forms, which primarily affects osmotic conditions and limits the water absorption of plants (Munns & Tester, 2008). On the contrary, excessive concentrations of bicarbonate contribute to salinization, increasing the share of exchangeable sodium in the composition of the soil adsorption complex. As sodium accumulation increases, clay particles collapse, soil aggregates lose their stability, infiltration decreases, and the destruction of the structure becomes more pronounced (Naida & Sumner, 1998; Sposito, 2008).

Recent advances in soil science have contributed to the widespread use of multidimensional statistical methods for studying complex chemical relationships in soil. Pearson correlation analysis is widely used to determine the direction and strength of linear relationships between AB and individual dissolved ions, allowing researchers to identify statistically significant relationships. However, the correlation analysis itself cannot determine the independent contribution of each variable when several ions act on its electrical conductivity at the same time (United States Salinity Laboratory Staff, 1954).

Because of this, multiple linear regression has become an important analytical tool for measuring the individual and combined effects of dissolved ions on the EC. This method allows you to divide the contribution of each predictor and consider the interaction between variables. In addition, the standardized regression coefficients (Beta) facilitate the direct comparison of the variables measured in different units of measurement and allow the identification of the ions that have the greatest impact on electrical conductivity.

The integration of these complementary statistical methods provides a more reliable and complete interpretation of the chemical composition of the soil solution, which is better than all other methods that consider it separately. This approach to analysis contributes to a deeper understanding of the mechanisms of ion interaction, identifies the dominant factors controlling the development of salinization, and reinforces predictive models that describe changes in the chemical properties of soil in various environmental and agricultural conditions. Thus, a comparative statistical assessment of base cations and anions is a highly effective approach to the study of mechanisms for determining electrical conductivity (Qadir et al., 2014). From the point of view of Basic Soil Science, such studies make a fundamental contribution to a more detailed understanding of Ionic interactions and internal processes that regulate the chemical balance of the soil. From a practical point of view, the results provide valuable scientific data to optimize irrigation management, improve land reclamation strategies, and promote sustainable use of land resources. In conclusion, it should be noted that the data obtained from a comprehensive statistical analysis allow for a more accurate diagnosis of soil salinization, allow for improved monitoring systems, and provide a solid foundation for the scientific management of agricultural lands subject to salinization (Visconti et al., 2010). The purpose of the study, the main goal of the presented scientific research, is to comprehensively assess the influence of the main cations and anions present in the soil solution on the formation of electrical conductivity (EC) using modern statistical methods. Within the framework of the study, the goal was set to compare the relative contribution of individual ions to the EC indicator, determine the strength and direction of these connections using correlation and regression analysis, and identify dominant Ionic components that are directly responsible for changes in electrical conductivity. In addition, the study provides for the control of the statistical significance of these dependencies, the identification of the main factors that control soil salinization, and the creation of scientific foundations for the interpretation of hydrochemical processes that regulate the distribution of salts through the accumulation of ions in the soil solution. The expected results will contribute to a better understanding of soil salinization processes and will contribute to the development of better regional assessment strategies, monitoring soil salinization and sustainable soil management.

To achieve the set goal of the study, the following tasks are intended to be performed:

- to determine the basic cation and anion composition of the soil solution and evaluate their concentrations;
- to analyze the patterns of change in electrical conductivity of soil solution;
- to evaluate the strength and direction of linear relationships between electrical conductivity and base ions based on Pearson correlation analysis;
- to build a multiple linear regression model for complex evaluation of factors affecting electrical conductivity;
- to determine the level of relative influence of each ion on the EC indicator using standardized Beta coefficients;
- to analyze the obtained statistical results comparatively and substantiate their scientific and practical significance in terms of assessing the level of salinity of soils.

2. Materials and Methods

Research area and sampling

The study was carried out in an area with semi-desert conditions, where salinization processes were observed. The selection of soil samples was carried out on the basis of the principle of a systematic grid; the sub-samples taken at each observation point were homogenized, and medium-mixed samples were prepared. Samples were taken from 0-20 CM and 20-40 CM layers of the soil profile; the ionic composition and electrical conductivity of the soil solution at these depths were comparatively studied.

Laboratory analysis

At the laboratory stage, a soil solution was prepared from soil samples according to the standard methodology, and its main physicochemical indicators were determined. The following parameters were determined during the analysis:

- electrical conductivity (EC, dS / m);
- Na⁺ (mmol/L)
- Ca²⁺ (mmol/L)
- Mg²⁺ (mmol/L)
- K⁺ (mmol/L)
- Cl⁻ (mmol/L)
- SO₄²⁻ (mmol/L)
- HCO₃⁻ (mmol/L)

The EC indicator was measured at a temperature of 25°C using a portable conductometer (Allison & Richards, 1954). United States Salinity Laboratory Staff, 1954). The concentration of IONS was determined by Standard titrimetric and photometric methods.

Statistical analysis methods

The data collected were analyzed by the following statistical methods:

- 1) Descriptive statistics. The average value, standard deviation, minimum and maximum indicators were calculated.
- 2) Pearson correlation analysis. The strength of the linear relationship between the variables is determined by the formula:

$$r = \frac{\sum(x - \bar{x})(y - \bar{y})}{\sqrt{\sum(x - \bar{x})^2 \sum(y - \bar{y})^2}}$$

3) Multiple linear regression model: The dependence of EC on ions was assessed by the following model:

$$EC = \beta_0 + \beta_1 Na^+ + \beta_2 Ca^{2+} + \beta_3 Mg^{2+} + \beta_4 K^+ + \beta_5 Cl^- + \beta_6 SO_4^{2-} + \beta_7 HCO_3^-$$

4) Standardized Beta ratios: The Relative Strength of the action of ions on the EC was determined.

5) Coefficient of determination (R²): The explanatory power of the model was assessed. Software used for statistical analysis:

- IBM SPSS Statistics 26
- Microsoft Excel 2019

3. Results and Discussion

Descriptive statistical results

During the study, the statistical indicators of the basic ions and electrical conductivity (EC) measured in the soil solution were as follows. High dispersion of EC and Na⁺ and Cl⁻ indicators indicates an uneven distribution of salinization in the area (Table 1).

Table 1. Descriptive statistics of soil solution indicators.

Parameter	Mean	Min.	Max.	Standart Deviation
EC (dS/m)	4.82	1.10	12.60	2.91
Na ⁺	28.4	6.2	75.0	18.7
Ca ²⁺	12.6	3.1	34.8	8.9
Mg ²⁺	9.8	2.0	25.4	6.1
K ⁺	2.4	0.5	6.8	1.5
Cl ⁻	30.7	5.4	82.1	20.2
SO ₄ ²⁻	18.3	4.0	49.5	11.6
HCO ₃ ⁻	7.9	1.2	21.3	5.4

Correlation analysis

Pearson correlation results show the strength of the connection between ions and EC. The change in EC is formed mainly by the action of Na⁺ and Cl⁻ ions (Table 2).

Table 2. Correlation coefficients between EC and ions.

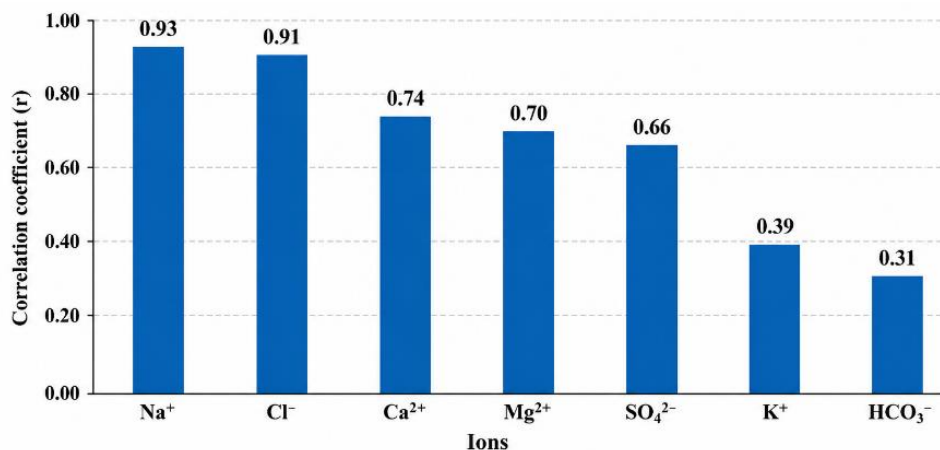
Parameter	Correlation Coefficient (r) with EC	Correlation Strength
Na ⁺	0.93	Very strong
Cl ⁻	0.91	Very strong
Ca ²⁺	0.74	Strong
Mg ²⁺	0.70	Medium
SO ₄ ²⁻	0.66	Medium
K ⁺	0.39	Weak
HCO ₃ ⁻	0.31	Weak

Regression model results

Multiple regression analysis yielded the following results:

Table 3. Standardized Beta ratios.

Variable	Standardized β Coefficient	Relative Effect
Na^+	0.41	The highest
Cl^-	0.38	High
Ca^{2+}	0.21	Medium
Mg^{2+}	0.18	Medium
SO_4^{2-}	0.15	Medium
K^+	0.09	Weak
HCO_3^-	0.07	Weak



The graph shows the strongest positive correlation of EC with Na^+ and Cl^- ions. Ca^{2+} , Mg^{2+} and SO_4^{2-} ions show a moderate correlation. K^+ and HCO_3^- ions show a weak correlation.

Figure 1. Correlation coefficient (Pearson r) between electrical conductivity (EC) and ions.

Figure 1 compares the correlation strength of the major ions with electrical conductivity (EC):

- Strongest correlation: Na^+ and Cl^-
- Moderate correlation: Ca^{2+} , Mg^{2+} , and SO_4^{2-}
- Weakest correlation: K^+ and HCO_3^-

The results obtained indicate that the electrical conductivity (EC) of the soil solution is governed by a complex system of dissolved ions. However, the statistical analyses demonstrated that sodium (Na^+) and chloride (Cl^-) ions are the dominant factors influencing EC. These findings suggest that:

- Soil salinity is primarily associated with the accumulation of sodium chloride (NaCl)-type salts.
- Although calcium (Ca^{2+}) and magnesium (Mg^{2+}) contribute to maintaining soil structural stability, their influence on EC is comparatively limited.
- Potassium (K^+) and bicarbonate (HCO_3^-) play secondary roles in determining the electrical conductivity of the soil solution.

Author's contribution

The sole author is responsible for conceptualizing, collecting, and analyzing data, and writing and editing the manuscript.

Conflict of Interest

The authors declare no conflicts of interest.

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