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Assessing Leaching Requirement an Ameliorated Saline Soil in a Lysimeter Experiment

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ABSTRACT

Soil salinity problems in the coastal hinterland region of East Java diminish agricultural development and land productivity. Soil leaching is expected to reduce soil salinity. This study investigated the effectiveness of different ameliorant compositions and leaching requirements (LR) in the leaching process. The experiment involved applying ameliorants (T) and leaching (L) treatments to lysimeters filled with saline soil. The ameliorant treatments included biochar, organic matter, and gypsum. The results showed the leaching requirement capacity to reduce electrical conductivity from 5.7 dS m^{-1} to below 2 dS m^{-1}. Leaching for T0 (without ameliorants) and T1 (10 Mg ha^{-1} of biochar) required 943 mm of water, while T2 (20 Mg ha^{-1} of biochar) and T3 (40 Mg ha^{-1} of compost) required 1052 mm. The T4 (10 Mg ha^{-1} of compost and 2 Mg ha^{-1} of gypsum) necessitated 1154 mm of leaching water. The ameliorants' application and assortment increased the water demand for leaching. The findings indicated a consistent relationship between TDS and salinity, indicating the soil's dominant presence of salty ions.

Keywords: Biochar, leaching requirement, organic matter, soil ameliorant, soil salinity

INTRODUCTION

Saline soils are defined as soils with an electrical conductivity (EC) of > 4.0 dS m^{-1}, pH < 8.5, and Na-exchangeable < 15% with normal physical conditions. Saline soils with exchangeable Na > 15% are sodic saline soils (Abdel-Fattah, 2012). This kind of sub-optimal soil needs to be more productive under conventional management. In Indonesia, salinity spreads on agricultural land near the coast. This area stretches from Situbondo, Probolinggo, Lamongan, and Tuban in East Java. It is estimated that land near the coast vulnerable to salinity covers an area of 12,020 million ha or 6.20% of Indonesia's land area and will increase because of sea level rise due to climate change (Rachman et al., 2018). Salinization is one of the critical problems on near-coastal agricultural land in the north coastal area of Java today (Karolinoerita and Annisa, 2020; Mindari, 2009). The significant increase in the concentration of highly soluble salts (NaCl, Na_2CO_3, and Na_2SO_4) in the soil has a detrimental effect on plant growth and poses a risk to food security (Abdel-Fattah, 2012; Ibrarullah et al., 2019).

Salinity is a measure of the amount of salt dissolved in water. The salinity value can be obtained by dividing the milligrams of salt in a given sample by kilograms of water. Salinity better describes the activity of the primary ions that determine salinity, namely chloride, sodium, and magnesium (Christy et al., 2020). Control of salinity conditions in the soil surface, air, and soil profiles is part of sustainable soil and water management practices. Drip irrigation is considered the most efficient irrigation method, as it enables the distribution of precise amounts of water to a specific area of soil, thereby minimizing water loss (Friedman and Gamliel, 2021).

Saline soil reclamation is carried out to alleviate soil salt problems. Some practices include soil leaching, agronomic practices, crop rotation, different irrigation practices, soil drainage, and gypsum applications (Abdel-Fattah, 2012). Other research showed biological methods of salt soil removal by applying manure (Tagar et al., 2010) and biochar (Christy et al., 2020; Jin et al., 2018). However, the effectiveness of salt leaching is hindered by specific unfavorable soil properties, such as low permeability. To address this issue, adding gypsum and rice straw can significantly improve the efficiency of salt leaching (Abdel-Fattah, 2012).

The high salt activity in saline soil must be reduced to an acceptable level for plant growth. Applying gypsum ($CaSO_4.2H_2O$) can effectively support salt and sodium soluble leaching in saline-sodic soils (Abdel-Fattah, 2012). Adding gypsum to the water at intervals of four or six days improved efficiency when reclaiming saline-sodic clays compared to without gypsum (dos Santos et al., 2014). The improving efficiency can be attributed to the valuable nutrient source of calcium-based gypsum, which reduces the toxicity effect in saline-sodic soils (Hafez et al., 2015; Giovanna et al., 2012).

Biochar is a potential soil amendment and has been widely used for agriculture. Biochar can reduce soil Bulk Density (BD) by 3 to 31%, raise porosity by 14 to 64%, and increase available water by 4 to 130% (Batarseh, 2017; Edeh IG and O Mašek, 2022). Blanco-Canqui (2017) showed that the application of 10 Mg ha^{-1} of compost and 40 Mg ha^{-1} of corn stalk biochar on Alfisol clay soils was able to reduce Bulk Density (BD) (26.5%), increase porosity (9.2%), and increase the pores of available water (61.9%). Biochar reduces plant Na^+ absorption and salinity pressure in plants and increases soil organic carbon, cation exchange capacity, and plant growth (Safitri et al., 2018). The effectiveness of biochar increases as more biochar is applied. Decreased biochar particle size can increase water retention (Batarseh, 2017). The combined utilization of biochar and compost notably increased the $NH4^+$-N soil content, available phosphorus (P), and available potassium (K) (Steiner et al., 2008; Cao et al. 2017.

A lysimeter is a soil-filled medium for studying water balances with characteristics close to conditions in the field. Some types of research lysimeters include the shape of a cylinder with a surface area of 1 m^2 and 1.5 m^3 in volume (Schneider et al., 2021), a cylindrical mini lysimeter with a diameter of 0.33 m, a surface area of 0.009 m^2, and volume of 0.009 m^3 (Geerts et al., 2009). The studied soil is transferred into a lysimeter according to a monolith shape (Schneider et al., 2021) by digging up the soil and maintaining the physical characteristics of the field soil. The other method is inserting the soil sample sequentially following horizon order (Abdulkareem et al., 2015). The lysimeter always has a leachate container to hold the solution from the system. By analyzing the water balance obtained from the lysimeter, the ETc (crop evapotranspiration) for different stages of plant growth can be determined.

Understanding leaching requirements for saline-sodic soil under soil amendment is necessary (Silva et al., 2019; Tagar et al., 2010). Therefore, the research objective was to assess the effect of soil amendment on the leaching requirement of saline-sodic soil in a lysimeter experiment.

MATERIALS AND METHODS

The study was conducted in an open experimental field of the Faculty of Agriculture, University of Jember (08°09'44" S and 113°42'58" E, elevation 135 masl) from September to December 2022. Drip irrigation with a solar panel was applied with two 100 WP solar panels. The panels were connected with an MPPT-type Solar Charge Controller to a 12-volt 100 Ah VRLA Battery. The battery was connected to a 12 Volt, 100 watts DC Submersible Pump, inserted via a 6-inch PVC pipe into a water source at 4m from ground level. Pumped water was collected into a 1000-liter reservoir. The reservoir water was drained into the drip irrigation system with a 12 Volt DC 30 watts Submersible pressure pump, delivered to the lysimeter using 2 liters $hour^{-1}$ capacity.

Lysimeter Installation

The constructed lysimeter is a concrete cylinder with an outer diameter of 60 cm, a height of 50 cm, and a thickness of 5 cm. The lysimeter is placed on a base with a height of 50 cm of the same concrete material to obtain the height from above the ground. On the lysimeter's front side, a hole is made to insert a perforated 1-inch diameter PVC pipe for leachate flow (Figure 1). On top of the pipe was laid gravel covering the pipe, and the rest was filled with sand to a height of 5 cm to resist the ingress of soil into the pipe. A reservoir of 20 liters was placed above the ground to accommodate the leachate flow resulting from irrigation and precipitation.

The soil was collected from the northern coastal area around Asembagus District, Situbondo, East Java, which has been known to have characteristics such as saline soil with EC>4 dS m^{-1}. The soil was classified as *Fluvaquentic Endoaquepts* (FAO: *Fluvic, Cambisol Oxyaquic*). Around 30 kg of a disturbed soil sample from the Ap horizon (0-25 cm) and Bw (25-40 cm) were incorporated in the lysimeter. Five lysimeters were used in the study, with one lysimeter filled with soil from the Ap-horizon of a *Typic Eutrudept* soil for comparison. Table 1 provides an overview of the soil's essential physical and chemical characteristics.

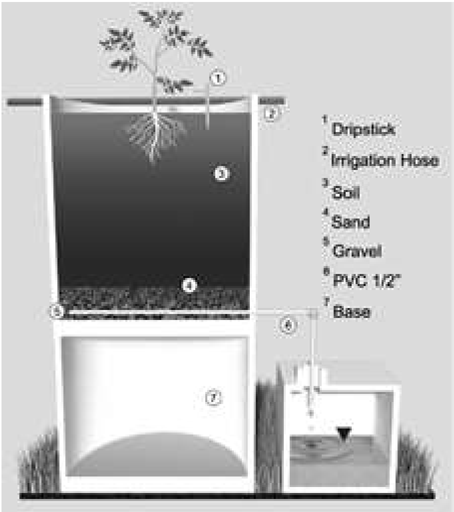

Figure 1. Lysimeter with leachate container.

There were five ameliorant treatments for every lysimeter. The addition of biochar and organic matter (ameliorant) was carried out at a dose of T0: without ameliorant, T1: 10 Mg ha^{-1} of biochar, T2: 20 Mg ha^{-1} of biochar, T3: 40 Mg ha^{-1} of compost, T4: 5 Mg ha^{-1} of biochar, 10 Mg ha^{-1} of compost and 2 Mg ha^{-1} of gypsum.

Leaching Process

The research began with the leaching process after a week of lysimeter incubation. Rainfall and drip irrigation from a water well source irrigated the soil during incubation. Positive water balance inside the lysimeter was collected in a 20-liter container (Figure 1). Soil samples were periodically taken using a careful insertion of a Stangenbohr soil auger into the lysimeter, ensuring not exceed a depth of 50 cm from the surface. The Electrical Conductivity of the leachate was directly measured using an EC meter. In contrast, the soil's electrical conductivity was measured by dissolving the soil in distilled water at a ratio of 1:2.5 (soil to water).

Leachate measurement due to leaching was carried out daily as leachate was produced. The EC was measured with an EC meter until the EC< 2 dS m^{-1} was obtained. The estimation of leaching requirements is calculated based on the equation proposed by Ayers and Wescot (1994) using Eq. (1). While the calculation considers the salinity of the irrigation water, the influence of crop tolerance is neglected in this study.

$$LR = \frac{EC_w}{5EC_e^* - EC_w} \dots\dots\dots\dots\dots\dots (1)$$

where EC_w denotes the electrical conductivity of the irrigation water.

The leaching requirement efficiency is generated based on the method Yang et al. (2019) proposed for steady-state conditions using Equations (2, 3, 4, 5).

Table 1. Physico-chemical characteristics of the soil in the lysimeter.

Nr.	Parameter	Hor. Ap (0-30 cm)	Hor. Bw1 (30-50 cm)
1.	Sand (%)	42	50
2.	Silt (%)	19	27
3.	Clay (%)	38	24
4.	Texture	clay loam	sandy clay loam
5.	Bulk Density (Mg m^{-3})	0.83	1.06
6.	Particle Density (Mg m^{-3})	2.44	2.45
7.	pH H2O (1:2.5)	7.09	7.62
8.	Electrical conductivity (dS m^{-1})	8.07	8.02
9.	Cation Exchange Capacity (cmol kg^{-1})	15.8	13.4
10.	Base Saturation (%)	32	40
11.	C-org (%)	1.27	1.14
12.	Ca (cMol kg^{-1})	0.77	0.90
13.	Mg (cMol kg^{-1})	2.6	2.9
14.	Na (cMol kg^{-1})	0.94	0.95
15.	K (cMol kg^{-1})	0.63	0.66
16.	Salinity Adsorption Ratio (mmol L^{-1})$^{1/2}$	0.72	0.69
	Exchangeable Sodium Percentage (%)	19	18

$$LF_w = \frac{D_{dw}}{D_{iw}} \dots\dots\dots\dots\dots.(2)$$

D_{iw} and D_{dw} are the depths of irrigation and drainage water (in cm).

$$LF_{EC} = \frac{EC_{iw}}{EC_{dw}} \dots\dots\dots\dots\dots.(3)$$

where EC_{iw} is the EC of irrigation water, and EC_{dw} is the EC of drainage water at the bottom of the root zone ($dS.m^{-1}$). The salt balance (SB) is calculated according to Wilcox and Resch (Yang et al., 2019) from the cumulative data as in Eq. (4).

$$SB = D_{dw}EC_{dw} - D_{iw}EC_{iw} \dots\dots\dots\dots\dots.(4)$$

where *SB* is the ratio of LF_w/LF_{EC}. When $LF_w > LF_{EC}$, then SB>0, which means drainage water carries more salts than salts applied from irrigation water; when LFw = LFEC, SB=0, which means steady-state, the amount of salts in drainage equals the number of applied salts from irrigation (Yang et al., 2019). Leaching efficiency (*LE*) can be determined from the ratio of the collected drained salt mass to the applied salt mass (Eq. 5) (Grismer, 1990).

$$LE = \frac{LF_w}{LF_{EC}} \dots\dots\dots\dots\dots.(5)$$

The results obtained from the calculations above illustrate the leaching requirement and the level of leaching efficiency performed.

RESULTS AND DISCUSSION

Soil EC in Lysimeter

The leaching with irrigation and rainfall has reduced the electrical conductivity from an average of 5.7 dS m^{-1} to under 2 dS m^{-1} (Figure 2). This study shows that soil ameliorant addition increases the leaching water requirement. The Lysimeter T0 (without ameliorant) and T1 (biochar 10 Mg ha^{-1}) require 943 mm leaching. Moreover, the T2 (biochar 20 Mg.ha^{-1}), T3 (40 compost Mg ha^{-1}) need 1052 mm, and T4 (10 Mg ha^{-1} biochar, 20 Mg ha^{-1} compost, and 2 Mg ha^{-1} gypsum) demand 1154 mm leaching water.

Applying 20 Mg ha^{-1} biochar and 40 Mg ha^{-1} compost augmented the leaching requirement by 109 mm compared to without ameliorant application. Utilizing 10 Mg ha^{-1} biochar and 20 Mg ha^{-1} compost increases leaching requirements by up to 211 mm. In the initial measurements, there was an increase in EC in the lower layer compared to the upper layer. This increase is likely to happen since the leaching was due to rain during one week of incubation, and EC measurements had not been taken.

The subsoil EC decline differs from treatment to treatment. The influence of T3 and T4 treatments causes a slighter decrease in EC in layers below 20 cm. The declining is due to the bases binding by organic matter and biochar in the soil that inhibits leaching. Similar findings were also reported by Chaganti and Crohn (2015), which showed that organic matter plays a crucial role as a soil ameliorant by enhancing soil structure, increasing water retention capacity, improving infiltration rate, promoting aeration, and enhancing soil porosity. Giovanna et al. (2012) showed that applying gypsum $CaSO_4$ during reclamation effectively decreased soil salinity and sodicity in Inceptisol and Mollisol soils. The electrical conductivity of the saturation extract (EC_e) reduced from 12.34 to 3.66 dS m^{-1}, while the exchangeable sodium percentage (ESP) decreased by 50.93% and 41.41%, respectively.

In non-saline soil with no amendments, leaching also reduced electrical conductivity (EC) (Figure 2). The EC decreased from 0.763 dS m^{-1} to 0.371 dS m^{-1} due to 395 mm of irrigation and rainfall. This finding highlights that the leaching of soil bases can be faster when the soil is deficient in organic matter or lacks biochar. Further comprehensive investigations on the leaching of soil bases should be undertaken using a similar approach. Most likely, the gypsum application in T4 inhibits after 502 mm leaching application (Figure 2). The specific sodium adsorption ratio (SAR) following the leaching process was not assessed. However, due to the calcium content of the gypsum used in T4, it is reasonable that the Na^+ cations in the exchange complex were displaced and replaced by Ca^{2+} ions.

These findings support the studies by Chaganti and Crohn (2015), applying organic manure resulted in a tremendous increase in organic carbon content and a significant decrease in electrical conductivity (EC) compared to using fertilizers alone. Additionally, Prapagar et al. (2012) showed that combining gypsum and biochar is the best application that affects better production for onions in saline soils. Therefore, biochar and organic matter positively affect the soil's physical and chemical characteristics of saline soils.

Leaching Requierement

To determine the decrease in lysimeter electrical conductivity (EC) caused by leaching, the average

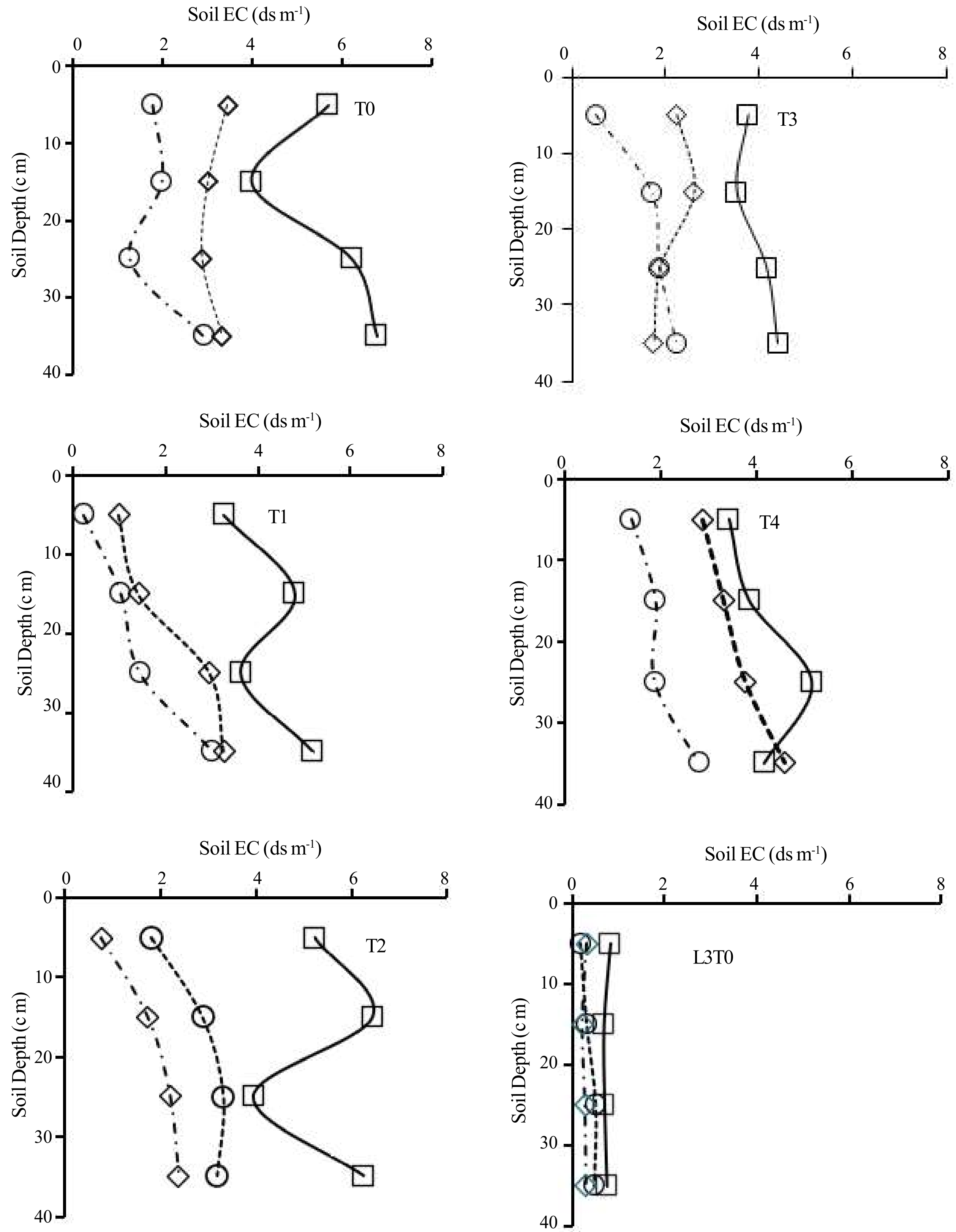

Figure 2. Distribution of Ec in the soil profile during the leaching process. L3T0 refers to the soil obtained from fertile farmland. : 0 mm, : 402 mm, : 943 mm (T0 and T1); : 0 mm, : 502 mm, : 1052 mm (T2); : 0 mm, : 402 mm, : 1052 mm (T3); : 0 mm, : 502 mm, : 1154 mm (T4); : 0 mm, : 315 mm, : 395 mm (L3T0).

soil EC was calculated from the surface layer up to a depth of 50 cm before and after the leaching procedure. The leaching process was halted once the average EC value of the final measurement dropped to less than half of 2 dS m^{-1}. The amount of water depth needed to achieve an EC value lower than 2 dS m^{-1} is called the Leaching Requirement (Figure 2).

Table 2 shows a substantial disparity between the actual leaching requirements and empirical calculations. This variance arises from the differences in defining the endpoint of the leaching process. This study aims to achieve an electrical conductivity (EC) value below 2 dS m^{-1} rather than relying on EC_{ei} as determined by the method proposed by Ayers and Wescot (1994).

The Leaching fraction for water fluxes (LF_w) exhibits a wide range of values (0.71-0.56) with leaching resulting in EC levels below 2 dS m^{-1} (Table 2), where a higher LFw indicates a more significant water requirement. Comparatively, the leaching fraction needed for T4 treatment is lower than T0, indicating higher efficiency. A similar pattern emerges when calculating leaching requirements based on LF_{ec}, notwithstanding values one-tenth of LF_w. This discrepancy is due to the utilization of EC_{iw} (0.31 dS m^{-1}) compared to the EC leachate, ranging from 4-5.5 dS m^{-1}. Consequently, LF_w is a better indicator for short-term leaching processes, while LF_{ec} is more reliable for long-term leaching.

Salt Balance, calculated as LF_w/LF_{EC}, determines leaching in saline soils. SB > 0 indicates salt transport into the soil, while SB < 0 occurs in fertile soil, not requiring salt leaching. However, SB magnitude is unrelated to leaching efficiency. Leaching Efficiency (LE) is highest in T0 (10.1), without ameliorants. T2 with biochar has the lowest LE (7.9), followed by T4 (biochar + compost + gypsum, LE 8.9). Biochar's cation exchange capacity retains salt cations, while compost is less effective. The application of ameliorants decreases LE and subsequently increases water-leaching requirements. These results implied that the application of ameliorant is preferably made after the leaching is completed.

When considering the outcomes of the Ayers and Wescot (1994) method, as demonstrated in the study conducted by (Silva et al., 2019), the leaching ranged from 402-502 mm (Figure 2). These findings aligned closely with the modeling results despite the measured EC values being higher than the values predicted by the model. Conversely, another study by Letey et al. (2011) presented contradictory findings, suggesting that the Ayers and Wescot (1994) model overestimated the measured results. Furthermore, Hoseini and Delbari (2015) proposed incorporating soil texture and exchangeable sodium factors into the leaching requirement calculations to address this issue. This adjustment led to a more reasonable agreement between the obtained leaching requirement and measured values.

Leachate

Applying soil ameliorants also affects leachate electrical conductivity (EC) (Figure 3). At the initial measurements, the EC of the leachate on T2 was 16.9 dS m^{-1}, which decreased to 4.5 dS m^{-1} through a leaching process of 1052 mm. Like the soil, the EC of the leachate exhibits a non-linear decline as leaching increases.

The impact of leaching water from rainfall and irrigation on leachate's electrical conductivity (EC) is indistinguishable. This finding implies that rainfall can be effectively utilized for leaching saline soils, and the leaching process can be carried out more efficiently during the rainy season.

Table 2. Comparison between measured Leaching Requirement and models.

Treatments	D_s	EC_{ei}	EC_{ef}	Empirical D_{iwe} (mm)	Measured D_{iwm} (mm)	LF_w	LF_{ec}	SB	LE
T0	50	5.7	2.0	359	942	0.71	0.070	2.348	10.1
T1	50	4.2	1.4	368	943	0.57	0.068	1.938	8.5
T2	50	5.5	1.3	489	1052	0.45	0.056	1.793	7.9
T3	50	3.4	0.8	499	1052	0.58	0.063	2.107	9.2
T4	50	4.2	2.0	283	1154	0.56	0.063	2.047	8.9
L3T0	50	0.6	0.3	275	315	0.80	1.105	- 34	0.7

D_s: soil depth (cm); EC_{ei}: soil salinity before leaching (dS.m^{-1}); EC_{ef}: soil salinity after leaching (dS.m^{-1}); D_{iwe}: irrigation water's depth (cm); D_{iwm}: drainage water's depth (cm); LF_w: leaching fraction for water fluxes (-); LF_{ec}: leaching fraction for EC (-); SB: salt balance (-); LE: leaching efficiency (-).

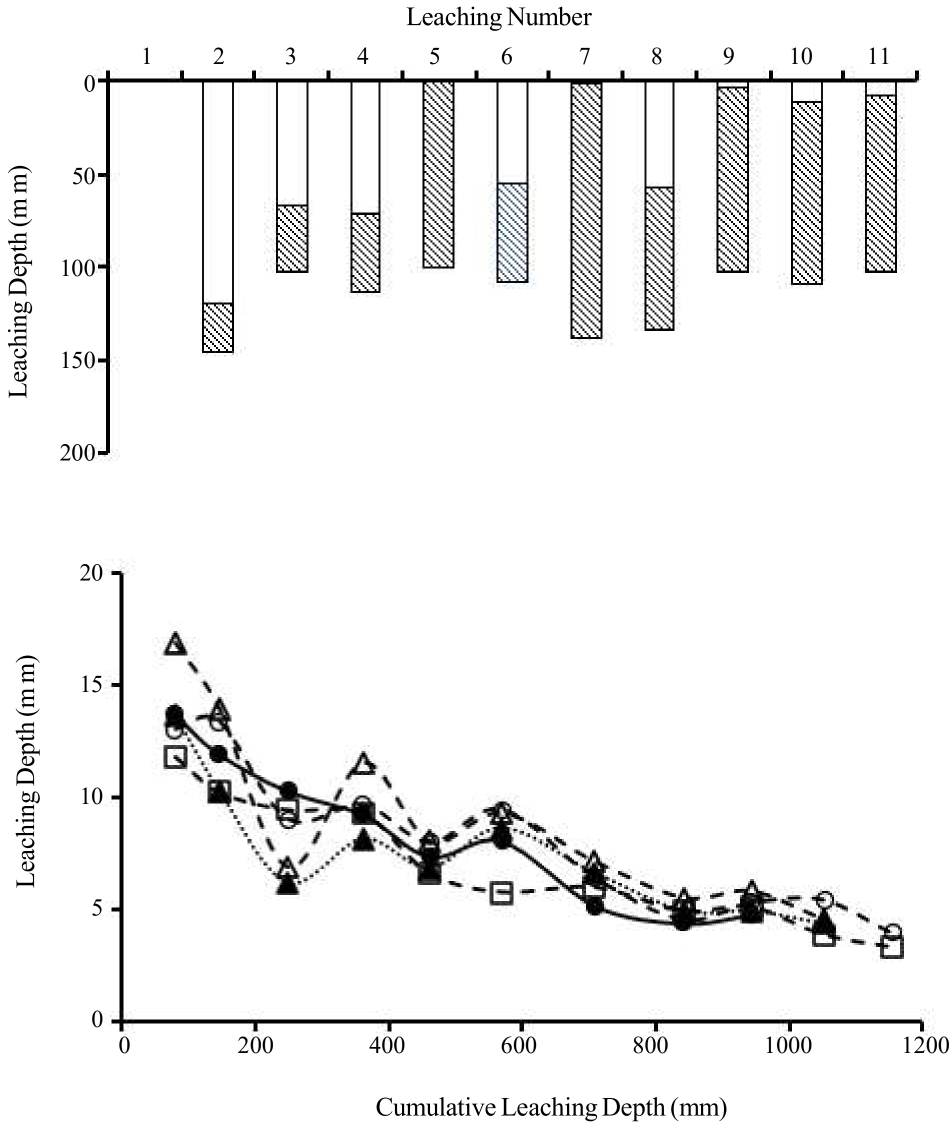

Figure 3. Leachate EC under Rainfall and Irrigation. □ : Rainfall (mm), ▧ : Irrigation (mm). —●— : L1T0, - -○- - : L1T1, - -△- - : L1T2, ······▲······ : L1T3, - -□- - : L1T4.

Total Dissolved Solid and Salinity

The Total Dissolved Solid (TDS) measures the concentration of organic and inorganic compounds in a soil solution, whereas EC characterizes the solution's capacity to conduct electric current. The TDS measured within the solution strongly correlates with the soil EC (Figure 4).

The correlation between TDS and EC in the soil is expressed by the equation TDS (ppm) = 497.1 × EC ($dS.m^{-1}$) (R^2 = 0.998). In contrast, Rusydi (2018) conducted water measurements and derived the formulas TDS = 0.65 × EC (R^2 = 0.97) and TDS = 0.89 × EC (R^2 = 0.96). These findings indicated higher values for TDS in water than those obtained in the current study, highlighting the discrepancy between EC measurement results in soil and water solutions.

The relationship between salinity and EC is expressed by the equation Salinity (ppm) = 381.5 × EC ($dS.m^{-1}$) (R^2 = 0.988) (Figure 4). The constant similarity between the TDS and salinity in this study suggests the prevalence of salty ions over other ions in the soil. However, further detailed investigation of the relationship between salinity and TDS is necessary.

The salinity characteristics of saline soils can be effectively described through electrical conductivity (EC) values. This EC value strongly correlates with total dissolved solids (TDS), representing the concentration of all soluble particles in groundwater and salinity, indicating the Na, Cl, and

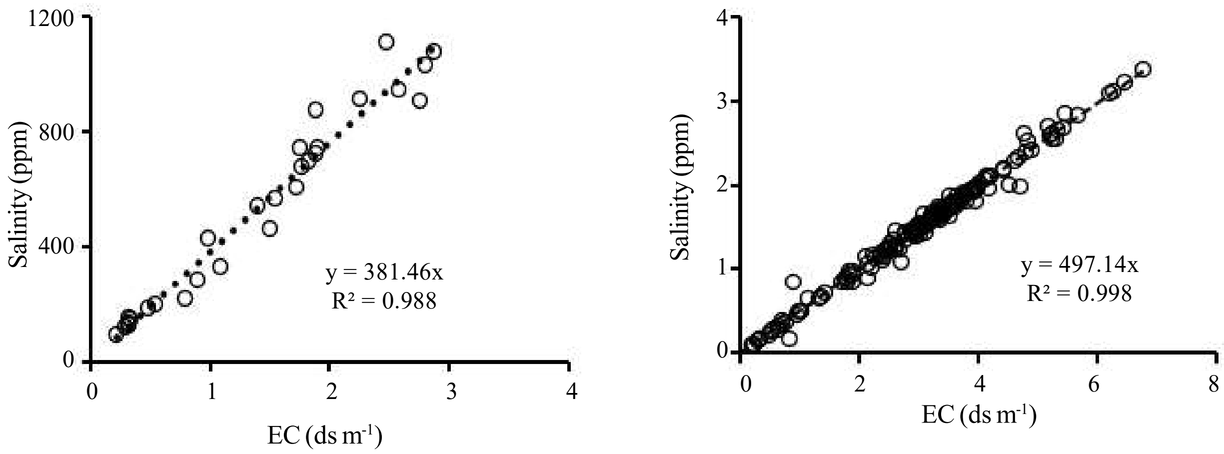

Figure 4. Relationship of Soil EC to Soil Salinity and TDS.

Mg ions (Chaganti and Crohn, 2015). The EC-TDS-Salinity indicator proves to be a crucial tool in characterizing saline soils. Interestingly, the study results revealed no correlation between soil pH and EC. The soil pH increased from 6.5 to 7.8 during the leaching process, indicating that the alteration of soil pH is not a reliable indicator for successful leaching.

CONCLUSIONS

Applying ameliorants increases the leaching water requirement (LR). Saline soil can be effectively leached using a combination of drip irrigation and rainfall, with a water requirement of 943 mm for a soil depth of 40 cm. The leaching process reduced the soil salinity (EC) from 5.7 dS m^{-1} to approximately 1.9 dS m^{-1}. The lysimeter without ameliorant and 10 Mg ha^{-1} of biochar application needed 943 mm leaching. The lysimeters treated with 20 Mg ha^{-1} of biochar and 40 Mg ha^{-1} of compost required 1052 mm.

Furthermore, the lysimeter treated with 10 Mg ha^{-1} of biochar, 20 Mg ha^{-1} of compost, and 2 Mg ha^{-1} of gypsum needed 1154 mm. However, there are variations in the leaching water requirements as measured by different empirical models. These findings emphasize the importance of applying soil ameliorants after completing the leaching process.

The strong correlation between EC-TDS-Salinity values highlights their significance as valuable parameters for leaching saline soils, with salty ions being predominant. The study found that there was no correlation between soil pH and EC. These findings indicate that soil pH is not a reliable indicator for successful saline soil leaching, as it increased during the process despite the lack of correlation with EC.

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