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Effect of gypsum for reclamation of tidal land soil using native halophyte plants in South Korea

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ABSTRACT

The objective of this study was to investigate the reclamation effect of 3 halophyte species, *Limonium tetragonum, Salicornia europaea* L., and *Suaeda japonica* Makino, with or without gypsum and under greenhouse conditions, on salt removal from saline-sodic soils of the reclaimed tidal lands of the southwest coast of South Korea. Despite cultivation of halophyte plants alone or with gypsum treatment for 2 years, saturated electrical conductivity (EC_e) and exchangeable sodium percentage (ESP) values of soils did not reach the reclamation criteria of 4 dS m^{-1} and 15%, respectively. The soil pre-treated with gypsum enhanced its characteristics by liberating the soil exchange complex Na^+ ions, which exited the exchange site due to the gypsum Ca^{2+} ions. The proposed phytoremediation technique showed fewer salinity and sodicity improvements than the chemical/physical salt removal methods presented in previous studies.

INTRODUCTION

In South Korea, tidal flats cover a total area of about 2,500 km^2, of which 2,100 km^2 are located on the west coast, while the remaining 400 km^2 are on the south coast. Over the past several decades, most of Korea's West Sea coastline has been engineered to reclaim tidal flats for arable land use (Koh and Khim, 2014). The reclaimed land is composed of saline-sodic soils with a high pH (6.5-7.9), high electrical conductivity (20-40 dS m^{-1}), high exchangeable sodium percentage (30-50%), and poor hydraulic conductivity. Despite these physio-chemical problems, the reclaimed tidal flats enhance the country's food production (Son et al., 2016).

The highly soluble and exchangeable salts, predominantly Na^+, in reclaimed tidal lands have a profound impact on soil chemical and physical properties as well as plant growth (Greene et al., 1988). Over time, the salts cause specific ion accumulation in plants. This can lead to ion toxicity or ion imbalance, and a continuous osmotic phase produced by the osmotic pressure of the saline soil prevents plants from water uptake (Munns and Tester, 2008). Saline-sodic soils are subject to severe structural degradation and show poor soil-water and soil-air interactions (Rengasamy and Olsson, 1991).

There are various physical and chemical methods that can remove salt from saline-sodic soils. Common reclamation methods include leaching, drainage, and gypsum treatment. Leaching reduces soil salinity by moving salts from the surface layers to the sub-surface. It also reduces water and nutrient use efficiency, requires high irrigation, and decreases root zone fertilizer availability (Diez et al., 1997). With leaching, there must be enhanced drainage to remove excess salt water (Dandekar and Chougule, 2010). In reclaimed tidal flats, water supply is insufficient, making it difficult to use drainage and leaching methods for soil salinity reduction. Gypsum ($CaSO_4 \cdot 2H_2O$) plays a significant role in the reclamation of saline-sodic soils by providing a Ca^{2+} to replace the exchangeable Na^+ from the colloid's cation exchange complex (Sharma and Minhas, 2005). However, gypsum application is challenging because of its long reclamation period and high cost (Filho et al., 2020). Phytoremediation is an alternative method using halophyte plants.

Halophyte plants can survive in salt environments due to adaptations including ion compartmentalization, osmotic

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Table 1. Physical and chemical properties of the soils before and after halophyte cultivation experiments.

Treatments		Before	After						
			Control	Lt	Se	Sj	Lt+G	Se+G	Sj+G
Soil texture			Silt loam						
Bulk density (kg m^{-3})		1.38±0.05	1.42±0.05	1.39±0.05	1.38±0.08	1.41±0.06	1.42±0.04	1.40±0.05	1.42±0.02
Organic carbon (%)		1.01±0.09	0.99±0.08	1.29±0.06	1.23±0.09	1.22±0.04	1.26±0.06	1.30±0.08	1.26±0.05
CEC ($cmol_c$ kg^{-1})		7.36±0.14	7.45±0.20	7.52±0.34	7.41±0.17	7.48±0.21	7.45±0.11	7.46±0.18	7.54±0.14
pH (1:5H_2O)		7.83±0.03	7.70±0.01	7.63±0.03	7.70±0.08	7.58±0.05	7.37±0.04	7.49±0.04	7.43±0.17
EC_e (dS m^{-1})		13.7±0.2	10.2±0.1	7.7±0.1	9.2±0.1	8.8±0.5	5.6±0.3	6.6±0.3	7.2±0.1
Exchangeable cations ($cmol_c$ kg^{-1})	Na^+	9.3±0.3	7.1±0.2	3.2±0.4	5.5±0.5	4.5±0.5	2.5±0.1	4.4±0.6	3.8±0.2
	Ca^{2+}	2.1±0.1	1.8±0.1	1.5±0.1	1.8±0.1	1.8±0.1	3.1±0.1	3.2±0.0	3.2±0.1
	K^+	1.4±0.2	0.9±0.1	0.9±0.1	0.8±0.1	0.7±0.2	0.7±0.2	0.7±0.1	0.6±0.0
	Mg^{2+}	2.5±0.2	2.2±0.0	2.3±0.1	2.1±0.2	2.2±0.1	2.1±0.1	2.1±0.2	1.9±0.2
Cl^-		10.6±0.0	6.7±0.7	5.1±0.2	3.9±0.4	4.7±0.3	3.0±0.1	2.7±0.1	3.4±0.2
ESP (%)		126.4±2.8	95.7±2.2	43.0±3.7	74.2±4.8	59.7±5.4	34.0±1.2	58.9±5.8	50.4±1.8

Lt, *L. tetragonum*; Se: *S. europaea* L.; Sj, *S. japonica* Makino; Lt+G: *L. tetragonum* + gypsum; Se+G, *S. europaea* L. + gypsum; Sj+G: *S. japonica* Makino + gypsum.

adjustments, ion transport and uptake, antioxidant systems, redox status maintenance, and salt inclusion or excretion (Hasanuzzaman et al., 2014). Several authors have shown the potential of halophytic plants to exhibit greater salt accumulation in their tissues and higher reduction of salts from the saline-sodic soils (Chaudhri et al., 1964; Hamidov et al., 2007; Ravindran et al., 2007).

Phytoremediation techniques require plants with high salt uptake-accumulation rates, large biomass, and tolerance to a wide array of environmental conditions. Previous studies were conducted in arid or semi-arid regions. It is difficult, however, to apply subtropical or tropical halophytic plants to the Northeast Asian climate, which comprises four distinct seasons and is in the monsoon zone. Therefore, it is necessary to evaluate phytoremediation using halophytic plants specific to this region. We conducted a pot experiment under greenhouse conditions to assess 3 halophyte species, *Limonium tetragonum, Salicornia europaea* L., and *Suaeda japonica* Makino. We used saline-sodic soils from South Korea's southwest coastal reclaimed tidal flats with and without gypsum.

MATERIALS AND METHODS

Halophyte plant cultivation

Soils were collected from 0-30 cm depths of reclaimed coastal tidal flats located in Gyehwa-myeon, Buan-gun, and Jeollabuk-do, South Korea (35°79′45″N, 126°63′77″E) (Son et al., 2016). The soils have thin, dark gray, silt loam Ap horizons and were formed in recently reclaimed fluviomarine plain alluvium with a high salt content (NIAST, 2000). Table 1 shows the physico-chemical properties of the soils before and after halophyte plant cultivation experiments. After 2 years of cultivation experiments, the control showed slight reclamation effects from natural rainfall. The halophyte plants showed better reclamation effects than the control, indicating a positive effect of gypsum in reclamation. The gypsum treatment was enhanced due to the increased Ca^{2+} activity coefficient as a result of the increased ionic strength of the soil solution.

Closed bottom, 25 × 20 cm (internal dimensions) plastic pots were filled with 15 kg experimental soil. The experiment assessed reclamation of reclaimed tidal lands soil using 3 halophyte plants, *L. tetragonum*, *S. europaea* L., and *S. japonica* Makino, all with and without gypsum. Therefore, six treatments were executed in a randomized complete block design: *L. tetragonum, S. europaea* L., *S. japonica* Makino, *L. tetragonum + gypsum, S. europaea* L. + *gypsum*, and *S. japonica* Makino + *gypsum*.

Gypsum is a soil conditioner that uses chemical and microbial action to furnish Ca^{2+} to exchange with Na^+. Gypsum ($CaSO_4{\cdot}2H_2O$, 93% GR, passed through a #70 mesh sieve) was added to a final concentration of 30 g kg^{-1} (Son et al., 2016) to the 10% ESP recommended by US Salinity Laboratory Staff (1954) guidelines. Gypsum was mixed with soil before filling the pots. Cultivation experiments were conducted for two years from April to November in 2018 and 2019. The seeds of the 3 types of halophyte plants used in the experiment were collected from the experimental site in late November 2017. After sowing 20 seeds per pot in late April 2018, the growth was complete in late November 2018. Germination of the halophyte plants progressed from the 8th day after sowing, and the germination rate of all 3 types was about 80%. Final plant height was about 60 cm. Nutrients were not

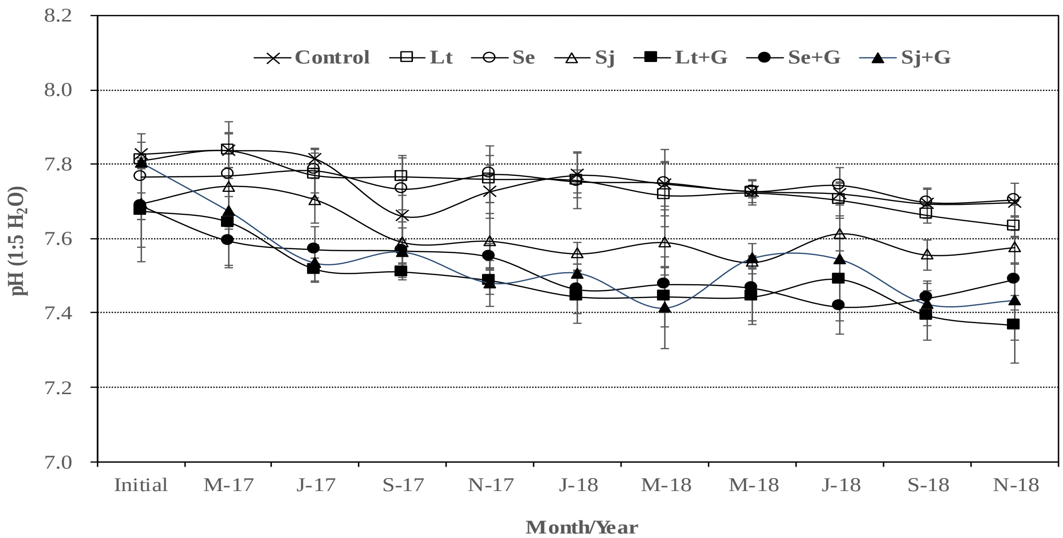

Figure 1. Changes of pH during reclamation of reclaimed tidal lands soil using native halophyte plants.

supplied during the experimental period, and weeds were removed manually. Water supplied to halophyte plants was maintained at water holding capacity of the soils. The experiments in 2019 were conducted using the same procedure as in 2018.

Soil analysis

Soil analysis details are provided by the authors' previous studies (Son et al., 2016; Kim et al., 2017). Soil samples were collected for determining physico-chemical properties and salinity once every 2 months at 0-10 cm depth. The collected soil samples were air dried, crushed, mixed, and sieved through a 2 mm sieve and analyzed using methods described by US Salinity Laboratory Staff (1954). The chemical properties evaluated were pH, saturated EC_e, soil organic carbon, cation exchange capacity (CEC), anions (Cl^-), and exchangeable cations (Ca^{2+}, Mg^{2+}, Na^+ and K^+). The pH and EC_e were measured in saturated paste and saturated paste extract, respectively. Soil organic carbon content was measured in ground, air-dried, soil samples using a carbon-nitrogen analyzer (PE-2400, USA). The CEC was measured using the ammonium acetate method, and chloride ions were measured using ion chromatography (Dionex™ ICS-6000 System, USA). Exchangeable cations were leached first with neutral 1 M ammonium acetate, and concentrations were determined using atomic absorption spectro-photometry (Perkin Elmer 2380, USA). The ESP was estimated using direct determination of exchangeable Na^+ and CEC, and physical properties of soil texture and bulk density were measured. Soil texture was classified by the pipette method. To determine bulk density, dry soil samples were collected in 57.73 cm^3 steel cylinders (Kim et al., 2017).

Statistical analysis

Statistical analysis was performed using the software SPSS 17.0. All data were analyzed using one-way analysis of variance (ANOVA), and the least significance difference (LSD) test was used to evaluate significant differences between treatments at $P \leq 0.05$ (Son et al., 2016).

RESULTS AND DISCUSSION

Soil pH

The gypsum treatment significantly affected soil pH before halophyte planting ($P \leq 0.05$). Initial soil pH for *L. tetragonum* + *gypsum, S. europaea* L. + *gypsum*, and *S. japonica* Makino + *gypsum* was 7.67±0.14, 7.69±0.04, and 7.80±0.02, respectively, which decreased to 7.37±0.04, 7.49±0.04 and 7.43±0.17, at the end of the experiment. There was no significant difference between the control and treated plants ($P \leq 0.05$) (Figure 1).

Gypsum treatment led to replacement of Na^+ by Ca^{2+} in the soil exchangeable complex, decreasing soil pH. These results agree with those of Haynes and Naidu (1998).

Electrical conductivity (EC_e)

The main challenge with reclaimed tidal land is reducing

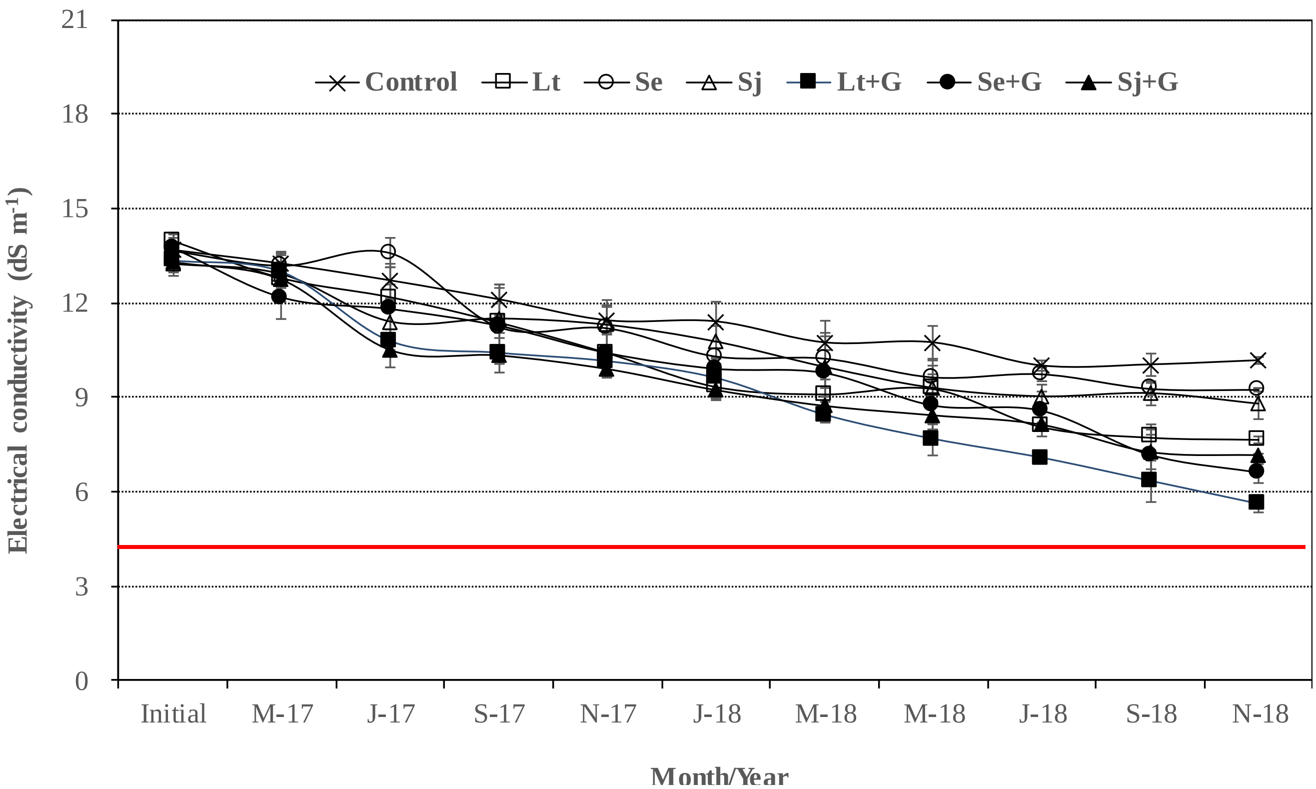

Figure 2. Changes of EC_e during reclamation of reclaimed tidal lands soil using native halophyte plants.

soil solution salinity. In experiments with only halophyte plants, soil EC_e decreased slightly from 13.7±0.2 to 10.2±0.1 dS m^{-1} for the control, 13.9±0.2 to 7.7±0.1 dS m^{-1} for *L. tetragonum*, 13.7±0.5 to 9.2±0.1 dS m^{-1} for *S. europaea* L., and 13.2±0.4 to 8.8±0.5 dS m^{-1} for *S. japonica* Makino. Overall, use of halophyte plants increased reclamation by about 10% compared to the control. With gypsum, the soil EC_e at the experiment end was 5.6±0.3, 6.6±0.3, and 7.2±0.1 dS m^{-1} for *L. tetragonum* + *gypsum*, *S. europaea* L. + *gypsum*, and *S. japonica* Makino + *gypsum*, respectively (Figure 2). Adding gypsum before planting the halophytes increased reclamation by about 30% compared to the control. The reclamation effect was higher for soils treated with gypsum before halophyte planting than in the treatment with only halophyte planting ($P \leq 0.05$). Regardless, none of the EC_e values reached the reclamation criteria (EC_e = 4.0 dS m^{-1}). However, it is estimated that the EC_e values in the reclaimed tidal lands soil can be reduced to the reclamation criteria after cultivating halophyte plants long-term after gypsum treatment. The plants in the gypsum-treated soils enhanced the soil by liberating Na^+ on the soil exchange complex for replacement with Ca^{2+} from applied gypsum. These results agreed with the findings of Qadir and Oster (2002), who stated that plants tolerant to salinity can be used to remove salts through their aboveground biomass.

Cations

Ca^{2+}, Mg^{2+}, and K^+ did not differ significantly by plant or gypsum treatment ($P \leq 0.05$) (Figures 3, 4 and 5). Compared to the control, soils with halophyte plants showed a remarkable cation decrease due to absorption-translocation by halophyte plants, particularly for Na^+. In the control, initial Na^+ concentration decreased by 23%, from 9.3±0.3 to 7.1±0.2 cmol kg^{-1}. In the plant pots, initial Na^+ concentration was 9.7±0.3, 9.2±0.1, and 9.5±0.2 cmol kg^{-1} for *L. tetragonum, S. europaea* L., and *S. japonica* Makino, respectively. By the end of the experiment, Na^+ concentration had decreased to 3.2±0.4 cmol kg^{-1} (67% reduction compared to control), 5.5±0.5 cmol kg^{-1} (40%), and 4.5±0.5 cmol kg^{-1} (53%) for the same plants, respectively. In the plants with gypsum-treated soil, initial Na^+ concentration for *L. tetragonum, S. europaea* L., and *S. japonica* Makino was 9.6±0.1, 9.4±0.3, and 9.4±0.2 cmol kg^{-1}, respectively, and decreased to 2.5±0.1 cmol kg^{-1} (74%), 4.4±0.6 cmol kg^{-1} (53%), and 3.8±0.2 cmol kg^{-1} (60%) by the experiments' end. The soil Na^+ ion concentration decreased in the order of *L. tetragonum* > *S. japonica* Makino > *S. europaea* L. (Figure 6). *L. tetragonum* is a broad-leafed plant characterized by thick, creeping roots. It is presumed that sodium absorption is higher in *L. tetragonum* than the other halophytes because

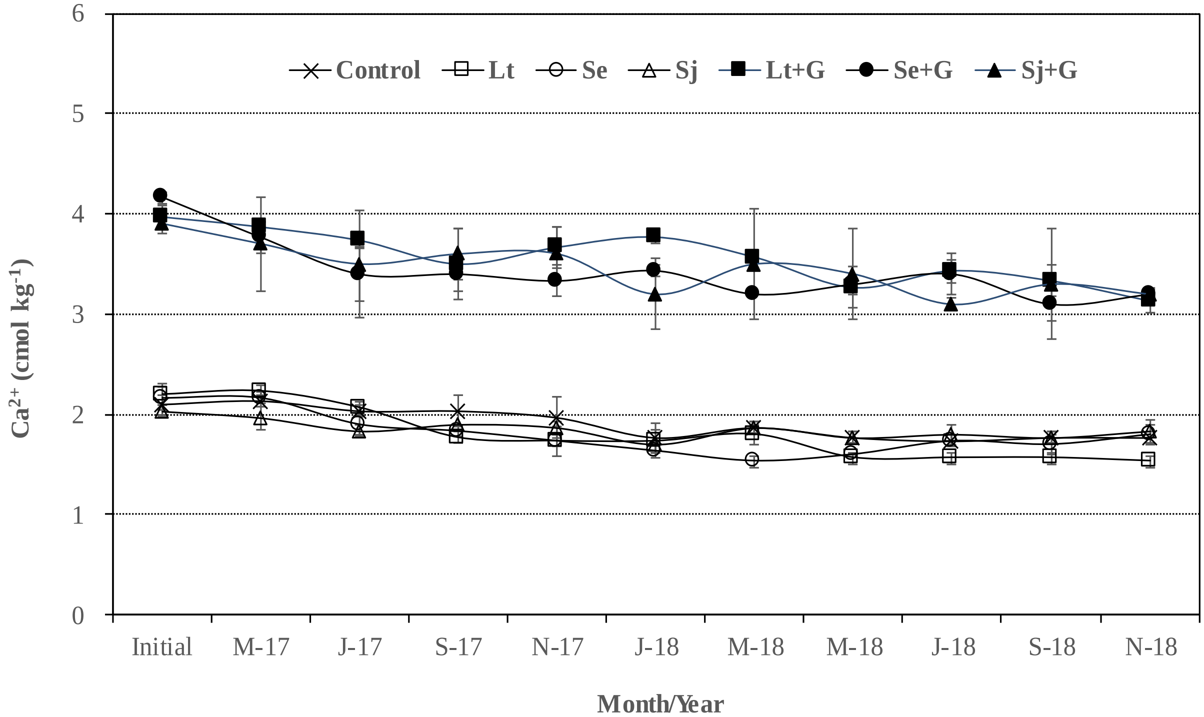

Figure 3. Changes of Ca^{2+} ion during reclamation of reclaimed tidal lands soil using native halophyte plants.

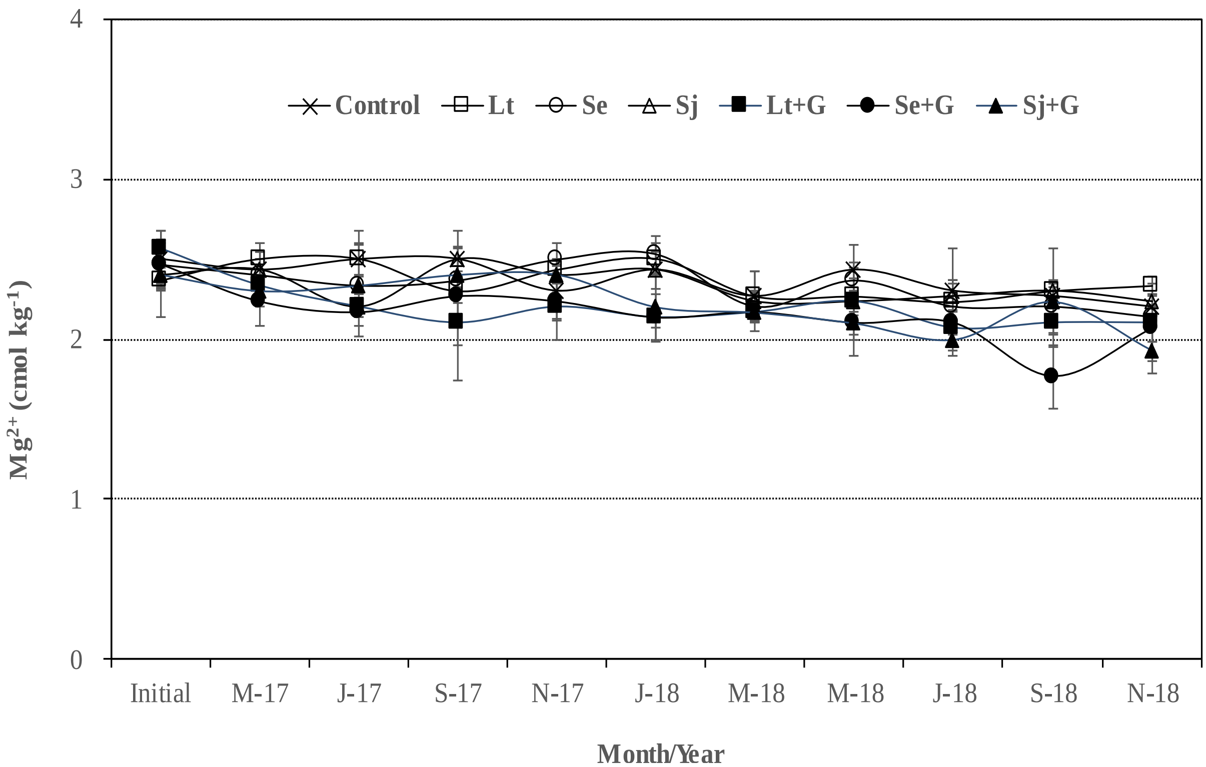

Figure 4. Changes of Mg^{2+} ion during reclamation of reclaimed tidal lands soil using native halophyte plants.

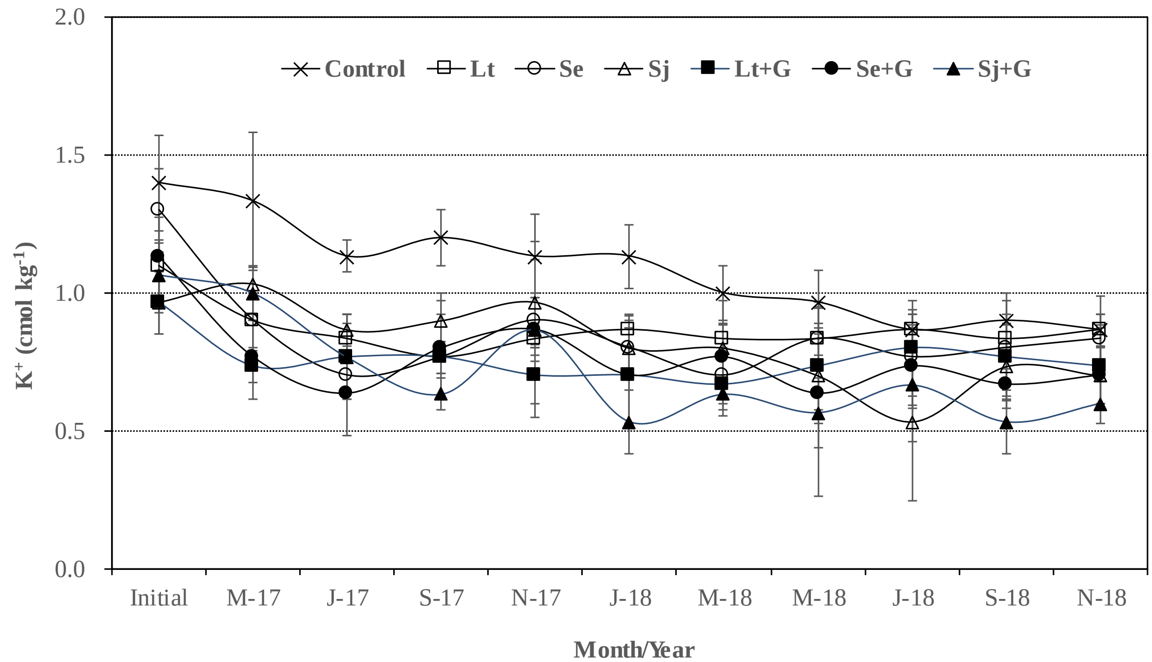

Figure 5. Changes of K^+ ion during reclamation of reclaimed tidal lands soil using native halophyte plants.

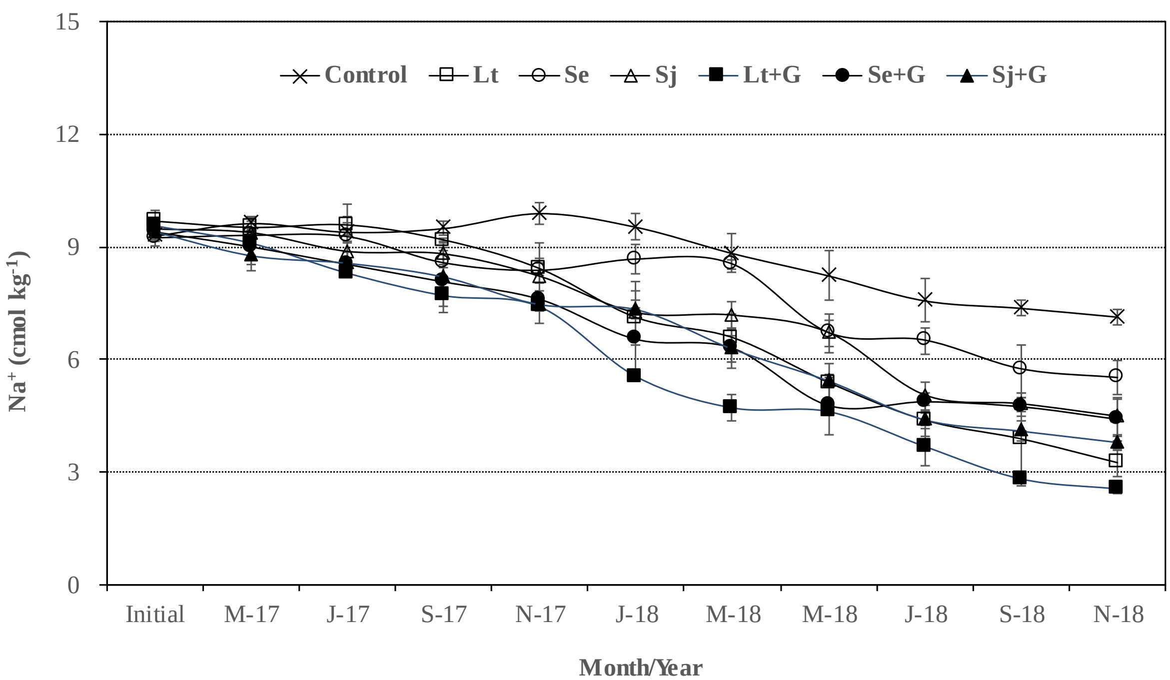

Figure 6. Changes of Na^+ ion during reclamation of reclaimed tidal lands soil using native halophyte plants.

of its active initial growth. The Na^+ ion reduction was slightly higher in soil with gypsum treatment before halophyte planting.

Chloride ion (Cl^-)

The initial Cl^- ion concentration decreased by 37% in the

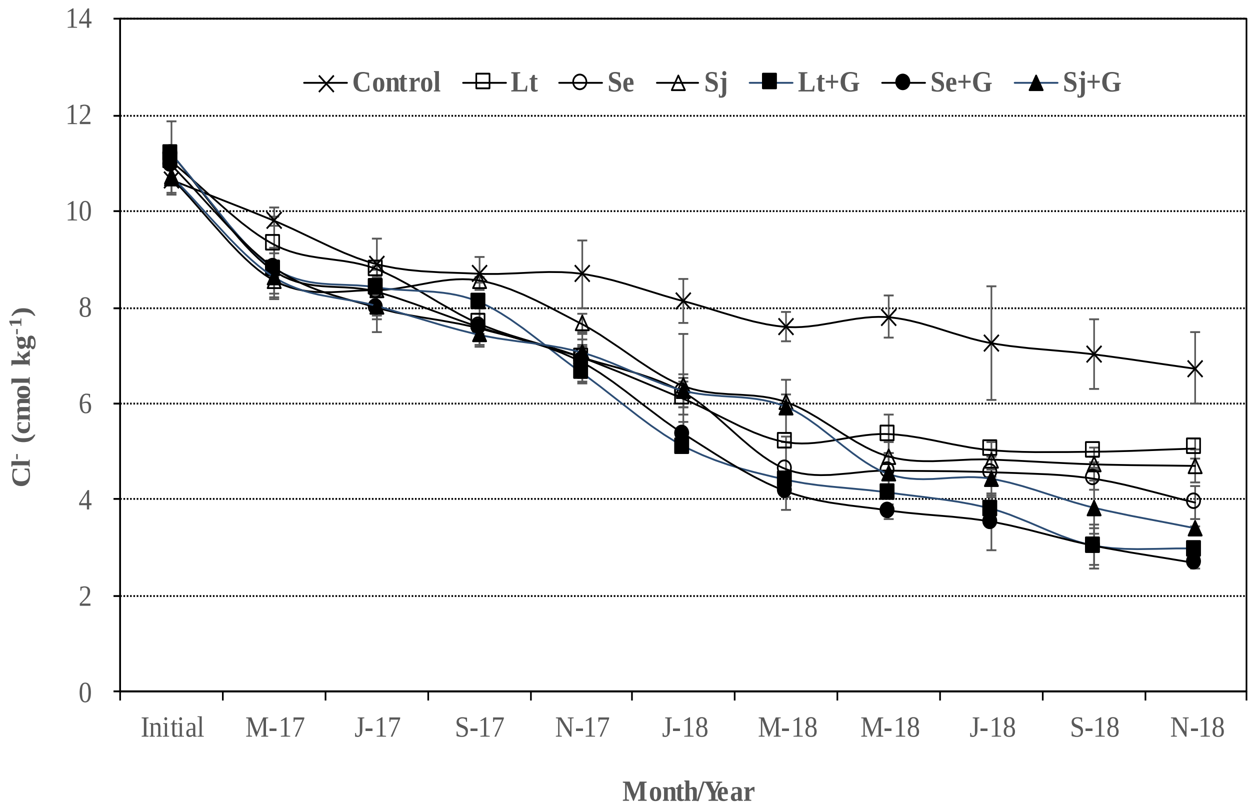

Figure 7. Changes of Cl^- ion during reclamation of reclaimed tidal lands soil using native halophyte plants.

control, from 10.6±0.1 to 6.7±0.7 cmol kg^{-1}. Initial Cl^- ion concentration in soils with *L. tetragonum, S. europaea* L., and *S. japonica* Makino was 11.0±0.2, 11.2±0.7, and 10.7±0.4 cmol kg^{-1}, respectively. By experiment end, the values decreased to 5.1±0.2 cmol kg^{-1} (53% reduction compared to control), 3.9±0.4 cmol kg^{-1} (65%) and 4.7±0.3 cmol kg^{-1} (56%), respectively. In the plants with gypsum-treated soil, initial Cl^- ion concentration was 11.2±0.2, 11.0±0.3, and 10.7±0.4 cmol kg^{-1} for *L. tetragonum, S. europaea* L., and *S. japonica* Makino, respectively. By the experiment's end, this value decreased to 3.0±0.1 cmol kg^{-1} (73%), 2.7±0.1 cmol kg^{-1} (75%), and 3.4±0.2 cmol kg^{-1} (68%), respectively. The soil Cl^- ion concentration decreased in the order of *S. europaea* L. > *L. tetragonum* = *S. japonica* Makino (Figure 7). The reduction of Cl^- ions by halophyte plants was slightly increased by gypsum treatment before planting.

Exchangeable sodium percentage (ESP)

The main index for assessing soil sodicity is ESP (US Salinity Laboratory Staff, 1954). For plants whose soil was pre-treated with gypsum, ESP decreased by 53 to 74% (34.0±1.2 to 58.9±5.8%) compared to the control (95.7±2.2%) (Figure 8). Sodicity improved in the order of *S. europaea* L. > *L. tetragonum* > *S. japonica* Makino. Even after 2 years, none of the soil ESP values reached sodicity criteria (ESP = 15%), the critical level described by the US Salinity Laboratory Staff (1954).

Gypsum decreased sodicity by reducing ESP. The Ca^{2+} ions improve the soil structure through cationic bridging with clay particles (Qadir et al., 1996). The gypsum can improve physical soil properties by enhancing salt leaching (Ahmad et al., 1990; Qadir et al., 1992). These results agree with the findings of Qadir and Oster (2002) and Qadir et al. (2007), who show that halophyte plants increase calcite dissolution through their root activity (Son et al., 2016). Several authors have shown other halophytic plant species to contribute to saline-sodic soil reclamation (for example, *Suaeda fruticose, Sesuvium portulacastrum, Portulaca oleracea, Arthrocnemum indicum*, *Tamarix aphylla*, and *Atriplex nummularia*) (Chaudhri et al., 1964; Ravindran et al., 2007; Hamidov et al., 2007; Rabhi et al., 2010).

Dry weight and ionic concentration

Plant dry weight at the end of the experiment in 2018 year

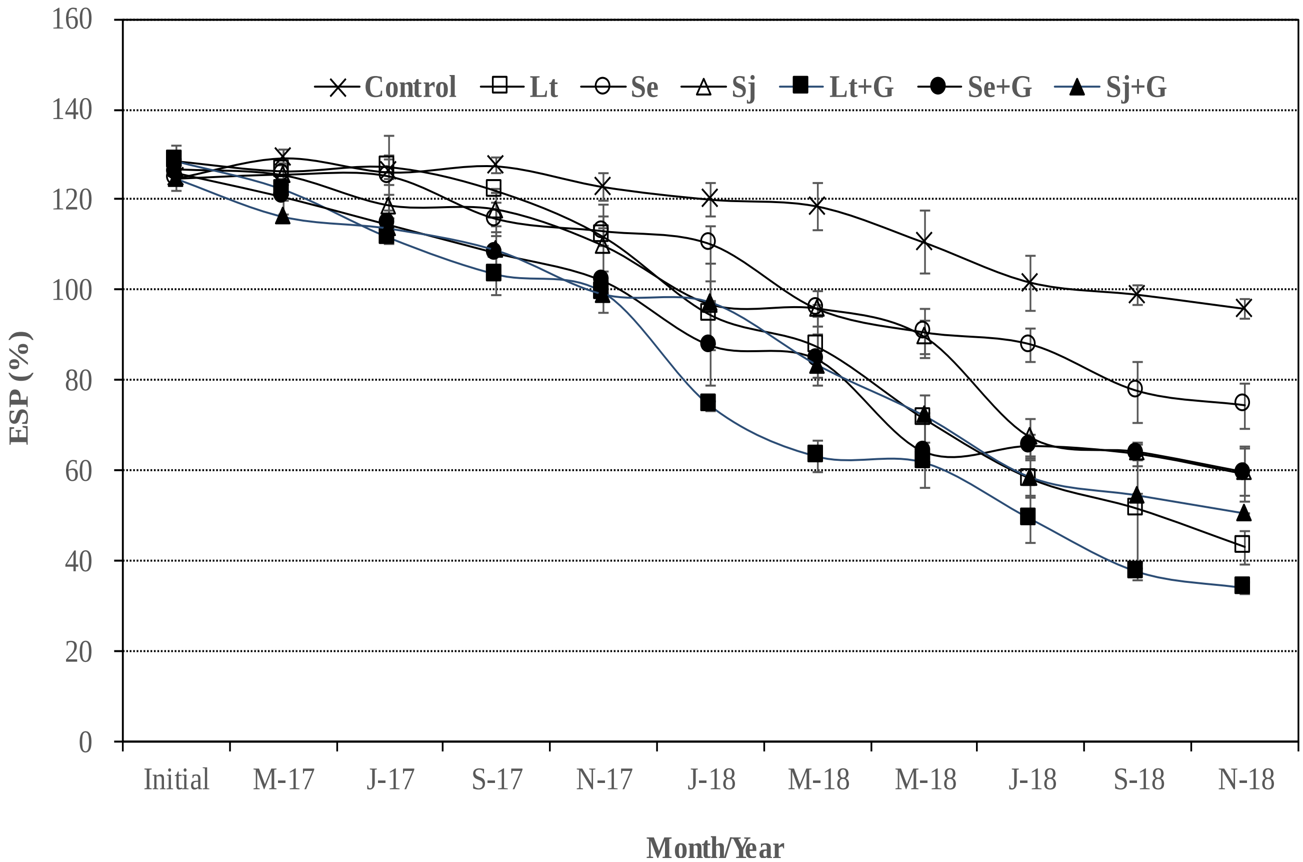

Figure 8. Changes of ESP during reclamation of reclaimed tidal lands soil using native halophyte plants.

was 23.4±1.2, 12.6±0.8, 18.4±0.9, 27.5±1.4, 13.7±1.8, and 20.1±1.2 g pot^{-1} for *L. tetragonum*, *S. europaea* L., *S. japonica* Makino, *L. tetragonum* + gypsum, *S. europaea* L. + gypsum, and *S. japonica* Makino + gypsum, respectively. As *L. tetragonum* produced more biomass than *S. europaea* L. and *S. japonica* Makino, its high dry weight likely is due to its comparatively thicker roots and greater biomass. There was no significant difference in dry weight of plants between 2018 and 2019.

The significant soil salinity decrease is reflected by the large amount of soluble ions, particularly Na^+ and Cl^-, removed through uptake by halophyte plants (Rabhi et al., 2010). In 2018, 13.7±0.4, 11.9±0.9, 12.2±0.5, 14.3±0.7, 12.2±0.8, and 14.4±0.7 g kg^{-1} of Na^+ were removed by *L. tetragonum*, *S. europaea* L., *S. japonica* Makino, *L. tetragonum* + gypsum, *S. europaea* L. + gypsum and *S. japonica* Makino + gypsum, respectively. Chloride ion removal followed a similar trend, ranging from 18.9±0.8 to 21.1±0.8 g kg^{-1} (Table 2). The high absorption of Na^+ and Cl^- in *L. tetragonum* plants is driven by enhanced level of Ca^{2+} in soil solution to replace Na^+ in the cation exchange complex (Qadir et al., 2007). This process was enhanced by $Ca2^+$ application within the root zone.

Conclusion

The reclamation effect in the reclaimed tidal lands soil was better with gypsum treatment before halophyte planting than in the treatment with only halophyte plants ($P \leq 0.05$). The halophytes in pre-treated soil liberated Na^+ ions from the soil exchange complex due to the Ca^{2+} from applied gypsum. Even after 2 years, the soil EC_e and ESP values did not reach the respective 4 dS m^{-1} and 15% reclamation criteria regardless of plant species or soil treatment (US Salinity Laboratory Staff, 1954). The limitations of this study was performed in the pot experiments under controlled conditions. Therefore, the authors will conduct long-term experiments under field conditions to elucidate the phytoremediation effect of native halophyte plants in saline-sodic soils.

ACKNOWLDEGEMENTS

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Table 2. Dry weight and ionic concentration for halophytes species.

Treatment	DW (g pot^{-1})		Ions removal from soil by plant (g kg^{-1})									
			Na^+		Mg^{2+}		Ca^{2+}		K^+		Cl^-	
	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018
Lt	23.2+1.1[a]	23.4+1.2[b]	13.2+0.3[a]	13.7+0.4[a]	5.6+0.2[a]	5.7+0.3[a]	1.9+0.2[c]	1.8+0.2[d]	0.8+0.2[a]	0.9+0.1[a]	19.3+0.7[a]	19.2+0.9[a]
Se	11.6+0.7[c]	12.6+0.8[d]	12.1+1.1[b]	11.9+0.9[b]	5.4+0.3[a]	5.5+0.3[a]	1.5+0.1[c]	1.7+0.1[d]	0.6+0.2[a]	0.7+0.2[a]	19.4+0.8[a]	18.9+0.8[a]
Sj	17.6+1.6[b]	18.4+0.9[c]	11.2+0.8[b]	12.2+0.5[b]	5.5+0.3[a]	5.0+0.9[a]	1.8+0.1[c]	1.8+0.1[d]	0.7+0.1[a]	0.8+0.1[a]	20.1+0.3[a]	19.7+0.8[a]
Lt+G	25.8+0.6[a]	27.5+1.4[a]	14.4+0.6[a]	14.3+0.7[a]	5.9+0.4[a]	5.9+0.1[a]	4.3+0.2[a]	4.7+0.1[a]	0.8+0.1[a]	0.9+0.2[a]	21.1+0.8[a]	20.9+0.4[a]
Se+G	12.3+1.6[c]	13.7+1.8[d]	12.0+1.0[b]	12.2+0.8[b]	5.5+0.3[a]	5.6+0.3[a]	3.8+0.1[b]	4.0+0.1[c]	0.7+0.1[a]	0.8+0.1[a]	20.3+1.0[a]	20.0+1.8[a]
Sj+G	17.6+2.9[b]	20.1+1.1[c]	12.8+0.8[b]	14.4+0.7[a]	5.8+0.1[a]	5.8+0.2[a]	4.3+0.2[a]	4.4+0.1[b]	0.8+0.1[a]	0.8+0.1[a]	20.5+0.9[a]	21.1+0.8[a]

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