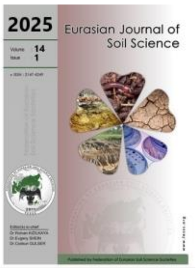
Eurasian Journal of Soil Science 2025, 14(1), 22 - 37

Eurasian Journal of Soil Science

Journal homepage : http://ejss.fesss.org



Phytoremediation of saline soils using *Glycyrrhiza glabra* for enhanced soil fertility in arid regions of South Kazakhstan

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Article Info

Received : 12.02.2024
Accepted : 06.10.2024
Available online: 12.10.2024

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Abstract

This study investigates the potential of *Glycyrrhiza glabra* (licorice) as a biological tool for reclaiming saline soils in the arid regions of South Kazakhstan. Licorice was cultivated over three growing seasons in weakly, moderately, and highly saline soils to evaluate its effectiveness in reducing soil salinity and improving soil fertility. The results show that licorice cultivation significantly reduced total salt concentrations and improved organic matter content in weakly saline soils. For instance, in some areas, total salts decreased by 50%, and humus content increased from 1.55% to 1.70%, indicating enhanced soil fertility. In moderately saline soils, the reduction in salt levels was less significant, and the plant's biomass yield dropped to 40 t/ha, compared to 50 t/ha in weakly saline soils. However, licorice still demonstrated its ability to moderately improve soil structure and nutrient availability. In strongly saline soils, licorice's effectiveness was considerably limited, with only minor reductions in salinity and a significant decrease in biomass yield to 20-30 t/ha. The study concludes that while *Glycyrrhiza glabra* is highly effective in reclaiming weakly saline soils, its impact in moderately and highly saline soils requires supplemental interventions, such as leaching, to optimize its phytoremediation potential. These findings suggest that integrating biological and traditional soil reclamation methods can offer a sustainable solution for managing saline soils in arid regions.

Keywords: *Glycyrrhiza glabra*, soil salinity, phytomelioration, biological reclamation, soil fertility, saline soils.

Introduction

Soil salinization is a critical environmental challenge, particularly in arid and semi-arid regions, where it drastically affects agricultural productivity and ecosystem health (Cuevas et al., 2019; Mukhopadhyay et al., 2021; Yin et al., 2022). Soil salinity occurs as a result of natural processes such as high evaporation rates, as well as anthropogenic activities, including improper irrigation techniques and the overuse of chemical fertilizers (Shrivastava and Kumar, 2015; Kumar and Sharma, 2020). Globally, an estimated 932 million hectares of land are impacted by salinity, with Central Asia being one of the most affected regions (Shahid et al., 2018; Duan et al., 2022). In countries like Kazakhstan, Uzbekistan, and Turkmenistan, large areas of irrigated land suffer from varying degrees of salinization, leading to reduced crop yields and increased soil degradation (Funakawa et al., 2000; Saparov, 2014; Pachikin et al., 2014; Otarov, 2014; Laiskhanov et al., 2016; Suska-Malawska et al., 2019, 2022; Zhang et al., 2019; Ma et al., 2019; Yertayeva et al., 2019; Kussainova et al., 2020; Liu et al., 2022; Bektayev et al., 2023).

In Kazakhstan, for example, approximately 41% of the country's agricultural land is affected by salinity, severely limiting its productive capacity (Saparov, 2014; Pachikin et al., 2014; Kussainova et al., 2020). Traditional methods of soil reclamation, such as mechanical leaching, involve the application of vast amounts of water to flush salts from the soil profile. While this method can be effective, it requires significant financial

doi : https://doi.org/10.18393/ejss.1565833
: https://ejss.fesss.org/10.18393/ejss.1565833
Publisher : Federation of Eurasian Soil Science Societies
e-ISSN : 2147-4249

and technical resources, and often leads to further environmental degradation due to the disposal of saline drainage water into natural water bodies. Given the economic and environmental constraints of these approaches, there has been increasing interest in biological methods of soil desalination (Stavi et al., 2021; Shaygan and Baumgartl, 2022).

Phytoremediation, the use of plants to remove or stabilize contaminants, is emerging as a sustainable and cost-effective alternative for managing saline soils (Kafle et al., 2022; Nainwal et al., 2024). Among the plants used for this purpose, *Glycyrrhiza glabra* (licorice) has shown considerable potential. Licorice is a perennial legume well-known for its high tolerance to salinity and drought conditions. It has been extensively used in Central Asia as a natural remedy for saline soils due to its ability to absorb and accumulate salts in its biomass, thereby reducing the overall salt content of the soil. Furthermore, licorice improves soil structure and fertility by enriching it with organic matter and enhancing microbial activity (Egamberdieva and Mamedov, 2015).

Research conducted in Uzbekistan and Kazakhstan has demonstrated that cultivating licorice in saline soils can result in significant reductions in soil salinity, improved soil fertility, and increased crop yields (Hayashi et al., 2003). In slightly saline soils, licorice has been shown to reduce salinity levels by 0.2 to 0.3 units, making it a viable option for sustainable soil management. Additionally, licorice contributes to the lowering of groundwater levels through its deep root system, which also helps reduce evaporation from the soil surface, further stabilizing the soil's moisture content (Egamberdieva and Mamedov, 2015).

Beyond its ecological benefits, licorice holds significant commercial value. Its roots are rich in glycyrrhizic acid, a compound widely used in the pharmaceutical and food industries, providing an economic incentive for farmers to adopt licorice cultivation as part of their crop rotation (Chin et al., 2007; Guo et al., 2015; He et al., 2019). This dual benefit-environmental and economic—makes licorice an attractive option for addressing the widespread issue of soil salinization in Central Asia (Khaitov et al., 2021, 2024).

The aim of this study is to evaluate the effectiveness of *Glycyrrhiza glabra* in reducing soil salinity and improving soil fertility under the specific conditions of slightly saline soils in Kazakhstan. By assessing the growth dynamics, biomass production, and impact on soil properties, this research seeks to contribute to the development of sustainable land reclamation practices that can be implemented in saline-affected regions.

Material and Methods

Study Area

The research was carried out in the Otrar district of the Turkestan region, South Kazakhstan. The study area is bounded by the ancient floodplain terrace of the Syrdarya River in the south and southeast, and by the Arys-Turkestan irrigation massif in the east and north. The experimental plots were selected in three farms: "Bakyt" (slightly saline soils), "Mukhit" (moderately saline soils), and "Birzhan" (highly saline soils). Each plot measured 200 square meters, resulting in a total experimental area of 600 square meters.

Experimental Design

The experiment aimed to assess the effectiveness of licorice (*Glycyrrhiza glabra* L.) cultivation for reducing soil salinity. Before planting, pre-plant soil preparation and moisture-charging irrigation were conducted to maintain soil moisture at 70-75% of field moisture capacity. Licorice was planted in rows, with a spacing of 70 cm between rows and 10-15 cm between plants within rows. The roots, 10-15 cm in length with a diameter of 1.0-1.5 cm, were planted vertically and horizontally to ensure proper root development.

Soil salinity levels were measured at the beginning and the end of the experiment using standardized methods. Additionally, groundwater levels were monitored to assess the desalinization impact of licorice cultivation. The experiment was replicated three times across the three levels of salinity.

Soil Sampling

Soil samples were collected at three different depths: 0–20 cm, 20–50 cm, and 50–100 cm across the experimental plots. Sampling occurred both at the start and end of the experiment to track changes in soil properties. The soil was sampled using a standardized auger, air-dried, crushed, and sieved through a 2 mm mesh to prepare for laboratory analysis.

Soil Analysis

The chemical analysis of soil samples was conducted using the following GOST standards for different parameters:

- Total Humus – Determined using the Tyurin method as per GOST 26213-91.

- Total Nitrogen – Assessed by the Kjeldahl method in accordance with GOST 26107-84.
- Hydrolyzable Nitrogen – Measured using the Tyurin-Kononova method (Tyrin, 1965).
- Mobile Phosphorus – Estimated by the Machigin method following GOST 26205-91.
- Exchangeable Potassium – Quantified using GOST 26205-91.
- Exchangeable Calcium and magnesium – Quantified using GOST 26487-85
- Total CO_3 determined by using GOST 34467-2018.

In addition to nutrient analysis, the ionic composition of the soil was analyzed for the following water extractable ions:

- CO_3^{2-}, HCO_3^- , Cl^-, SO_4^{2-}, Na^+, K^+ Ca^{2+}, Mg^{2+} determined by using GOST 26423-85, GOST 26428-85, GOST 26424-85, GOST 26425-85 and GOST 26427-85.

Additionally, the following properties were assessed:

- Total salts (Electrical Conductivity, EC) of the soil extracts to determine salinity, as per GOST 26423-85.
- Soil pH was measured in a 1:5 soil-to-water suspension, following GOST 26483-85.

Licorice Cultivation and Agricultural Management

Licorice Propagation and Planting

Licorice (*Glycyrrhiza glabra* L.) was propagated using rhizomatous cuttings, which were manually prepared by cutting them into sections of 15–30 cm. Each section had 2–3 buds to ensure optimal growth. The planting was carried out in early spring with row spacing of 70 cm, and a distance of 25–30 cm between plants. The rhizomes were planted at a depth of 10–15 cm, either vertically or horizontally, to promote proper root establishment and shoot development.

Soil Preparation

Before planting, the soil underwent deep plowing to a depth of 25–27 cm. Superphosphate and potassium salt were applied at a rate of 150–200 kg/ha, followed by ammonium nitrate at 100–150 kg/ha during soil preparation. This helped improve soil fertility and structure, ensuring better initial growth conditions for licorice.

Irrigation and Fertilization

In the first year of licorice cultivation, the fields were irrigated 3–4 times to help with root establishment. In the second year, irrigation was reduced to 2–3 times, depending on rainfall and the depth of the groundwater table. For fertilization, rotted manure at 2–3 t/ha was applied in the autumn, while ammophos was added at 150–200 kg/ha in the spring.

Weed Control and Maintenance

Weed control was carried out regularly during the growing season to minimize competition. Soil loosening was also performed to ensure proper root growth and soil aeration. In the first year, dry stems were pruned in the autumn to promote healthy new growth in subsequent seasons. By the second year, the above-ground biomass had reached 7–8 t/ha, and the root yield was around 25 t/ha. These measures contributed to the effective reclamation of saline soils, enhancing soil structure and fertility.

Measurement of Licorice Yield

The yield of licorice (*Glycyrrhiza glabra*) was measured as the total fresh biomass harvested from the experimental plots. At each designated harvest time, the entire above-ground portion of the plant was collected and weighed to determine the fresh weight. The yield was calculated as total biomass per hectare (t/ha), without distinguishing between root and stem components. This measurement focused on the total green mass of the plant. Yields were then compared across different salinity levels based on the total biomass collected from each area.

Results and Discussion

Impact of Licorice Cultivation on Soil Chemical Properties

The data in Table 1 reveal the seasonal changes in key agrochemical parameters of solonchakous sierozem-meadow soils across different salinity levels over the study period. By examining total humus content, nitrogen, phosphorus, potassium, and carbonates, the impact of licorice (*Glycyrrhiza glabra*) cultivation on soil fertility is analyzed.

Table 1. Seasonal Phytomeliorative Efficiency of Licorice on Agrochemical Parameters of the Root Zone of Solonchakous Sierozem-Meadow Soils

Point No	Depth, cm	Selection terms	Total humus, %	Total nitrogen, %	Hydrolysable nitrogen, mg/kg	Mobile P_2O_5, mg/kg	Exchangeable K_2O, mg/kg	Total CO_3, %
Weakly saline soils, Bakyt farm								
534	0-20	spring, 2019	1,55	0,112	42,0	37,0	480	9,55
		autumn, 2019	1,70	0,154	42,2	23,0	420	10,34
		autumn, 2020	1,70	0,154	42,2	23,0	420	10,34
535	0-20	spring, 2019	1,51	0,112	33,6	20,0	410	10,32
		autumn, 2019	1,32	0,098	39,2	16,0	410	10,27
		autumn, 2020	1,15	0,112	47,6	15,0	500	9,51
536	0-20	spring, 2019	1,62	0,098	39,2	18,0	430	10,70
		autumn, 2019	1,46	0,098	36,4	20,0	460	10,55
		autumn, 2020	1,46	0,098	58,8	17,0	470	9,55
537	0-20	spring, 2019	1,33	0,084	33,6	27,0	600	8,75
		autumn, 2019	1,70	0,140	39,2	25,0	540	9,33
		autumn, 2020	1,11	0,004	33,6	20,0	570	9,85
538	0-20	spring, 2019	0,88	0,084	36,4	12,0	540	10,25
		autumn, 2019	2,23	0,126	33,6	10,0	650	9,29
		autumn, 2020	1,36	0,112	42,0	33,0	870	9,75
Moderately saline soils, Mukhit farm								
539	0-20	spring, 2019	0,92	0,056	19,6	18,0	440	10,46
		autumn, 2019	0,52	0,042	33,6	10,0	460	10,68
		autumn, 2020	0,31	0,084	50,4	24,0	410	10,19
540	0-20	spring, 2019	0,29	0,070	28,0	9,0	380	10,98
		autumn, 2019	0,49	0,070	36,4	8,0	460	10,58
		autumn, 2020	0,38	0,084	39,2	14,0	380	10,43
541	0-20	spring, 2019	0,88	0,056	30,8	15,0	430	10,91
		autumn, 2019	0,28	0,098	36,4	13,0	440	10,65
		autumn, 2020	0,24	0,084	42,0	20,0	440	10,02
542	0-20	spring, 2019	0,44	0,042	19,6	27,0	400	10,87
		autumn, 2019	0,21	0,098	42,2	16,0	320	10,93
		autumn, 2020	0,45	0,070	39,2	33,0	440	8,49
543	0-20	spring, 2019	0,81	0,070	30,8	27,0	380	10,81
		autumn, 2019	0,52	0,070	33,6	10,0	370	10,72
		autumn, 2020	0,56	0,070	44,8	36,0	490	10,05
Strongly saline soils, Birzhan farm								
549	0-20	spring, 2019	0,70	0,098	19,6	57,0	600	11,05
		autumn, 2019	0,76	0,084	42,2	40,0	650	8,87
		autumn, 2020	0,52	0,084	39,2	43,0	610	8,73
550	0-20	spring, 2019	0,70	0,042	28,0	24,0	520	11,29
		autumn, 2019	0,45	0,070	39,2	32,0	590	9,15
		autumn, 2020	0,63	0,070	47,6	36,0	650	9,00
551	0-20	spring, 2019	0,92	0,098	25,2	38,0	580	9,42
		autumn, 2019	0,56	0,098	44,8	35,0	500	8,88
		autumn, 2020	0,42	0,098	28,0	30,0	630	9,34
552	0-20	spring, 2019	0,66	0,112	30,8	38,0	540	9,76
		autumn, 2019	0,52	0,084	47,6	25,0	520	9,19
		autumn, 2020	0,56	0,084	22,4	50,0	440	9,31
553	0-20	spring, 2019	0,52	0,070	28,0	73,0	540	8,96
		autumn, 2019	0,28	0,070	47,6	39,0	490	9,08
		autumn, 2020	0,24	0,070	30,8	33,0	510	9,68

Changes in Humus Content

The results show a significant increase in humus content in weakly saline soils, particularly in the 0-20 cm soil layer. For instance, at point 534, humus levels increased from 1.55% in spring 2019 to 1.70% by autumn 2020. This 9.7% increase can be attributed to the decomposition of licorice root biomass, which enriches the soil with organic matter. Similarly, other points in weakly saline soils (e.g., point 537) show comparable increases, indicating that licorice cultivation promotes the accumulation of organic matter in surface soil layers. This increase in humus enhances soil structure, water retention, and microbial activity, contributing to overall soil fertility improvement.

Nitrogen Content Dynamics

The total nitrogen content also showed fluctuations during the study, with a general increase in both weakly and moderately saline soils. For example, at point 536, total nitrogen levels increased from 0.098% in spring 2019 to 0.154% by autumn 2020. In contrast, at some points like 537, the nitrogen content slightly decreased in the first year before stabilizing by autumn 2020. The hydrolysable nitrogen levels followed a similar trend, particularly in weakly saline soils, where increases were observed by the end of the experiment. This suggests that licorice cultivation improves nitrogen availability over time, although results may vary depending on initial soil conditions.

Phosphorus and Potassium Availability

Mobile phosphorus (P_2O_5) and exchangeable potassium (K_2O) levels fluctuated throughout the study period. At point 534, phosphorus levels decreased from 370 mg/kg in spring 2019 to 230 mg/kg by autumn 2020, indicating that licorice plants might be absorbing significant amounts of available phosphorus for growth. Similarly, potassium levels showed a general decline in weakly saline soils, suggesting a high uptake by licorice plants, which is consistent with the plant's role in nutrient cycling. Despite these reductions in available P2O5 and K_2O, licorice's contribution to overall soil fertility through organic matter buildup seems to offset any negative impacts of nutrient depletion.

Carbonates and Salinity Influence

The carbonate (CO_3) content in weakly saline soils showed mixed results. At point 538, for example, carbonate levels decreased from 1.025% in spring 2019 to 0.975% by autumn 2020. This slight decrease in carbonates indicates that licorice may help reduce soil salinity by affecting the chemical composition of the soil. However, in moderately saline soils, the reduction in carbonate content was less pronounced, suggesting that higher salinity levels may limit the plant's ability to modify soil chemistry as effectively.

The results from Table 1 clearly demonstrate that licorice cultivation positively impacts the chemical properties of solonchakous sierozem-meadow soils, particularly in weakly saline areas. Increases in humus content and improvements in nitrogen levels highlight licorice's potential as a phytomeliorative crop that enhances soil fertility. However, reductions in available phosphorus and potassium in some areas suggest that nutrient management practices may need to be adjusted to ensure long-term soil productivity. Overall, licorice shows promise for improving soil health in weakly saline soils, but its impact in moderately saline conditions requires further optimization and management.

Seasonal Variations in Soil Ionic Composition

The data in Table 2 reveal seasonal variations in the concentrations of key ions, total salts, and pH levels across different soil depths (0-20 cm, 20-50 cm, 50-100 cm) in weakly saline soils cultivated with licorice (*Glycyrrhiza glabra*). These changes reflect the effects of licorice cultivation on the salinity profile and nutrient balance of the soil.

Total Salts and Soil Salinity Dynamics

The total salt content in the 0-20 cm soil layer showed a considerable increase across the study period, particularly at point 534, where the total salts rose from 0.327% in spring 2019 to 1.440% by autumn 2020. This marked increase can be attributed to the accumulation of salts due to evaporation and insufficient leaching, highlighting a challenge in salinity management despite licorice cultivation. Similar trends were observed at other points, where the total salt content in the topsoil consistently rose, indicating that while licorice may aid in soil structure improvement, it is not fully effective in reducing overall salinity.

Bicarbonates (HCO_3^-) and Carbonates (CO_3^{2-})

Bicarbonate (HCO_3^-) concentrations remained relatively stable, with minor increases across soil depths. For instance, at point 534, HCO_3^- levels rose from 0.044 meq/100g to 0.499 meq/100g in the topsoil. This moderate increase suggests that while bicarbonate does not fluctuate significantly with salinity changes, its presence can still contribute to soil alkalinity. Carbonate (CO_3^{2-}) ions were negligible throughout the study period, indicating that carbonate toxicity was not a significant issue in these soils.

Table 2. Seasonal phytomeliorative efficiency of licorice on the salt regime of solonchakous sierozem-meadow soils of pilot plots (meq 100 g^{-1})

Points No	Selection terms	Soil depth, cm	Total salts, %	HCO_3^-	CO_3^{2-}	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	Na^+	K^+	pH
Weakly saline, Bakyt farm												
534	spring, 2019	0-20	0,327	0,44	0,00	1,64	2,96	1,60	1,48	1,65	0,31	8,73
		20-50	0,355	0,39	0,00	2,23	3,03	1,70	1,73	2,17	0,05	8,91
		50-100	0,179	0,44	0,00	0,93	1,38	0,50	0,82	1,43	0,00	9,20
	autumn, 2019	0-20	0,344	0,56	0,00	0,54	3,93	1,65	1,15	2,00	0,23	8,39
		20-50	0,167	0,61	0,00	0,14	1,71	0,50	1,15	0,78	0,03	8,96
		50-100	0,156	0,64	0,00	0,17	1,46	0,25	0,99	1,00	0,03	9,16
	autumn, 2020	0-20	1,440	0,44	0,00	4,99	16,76	4,65	6,51	10,64	0,38	8,45
		20-50	0,871	0,52	0,04	1,92	10,62	1,68	3,16	8,19	0,03	8,59
		50-100	0,791	0,64	0,04	1,92	9,27	1,88	2,57	7,37	0,00	8,55
535	spring, 2019	0-20	0,492	0,44	0,00	0,85	6,15	2,60	2,47	2,17	0,20	8,90
		20-50	0,483	0,44	0,00	1,58	5,38	1,80	2,20	3,35	0,05	9,07
		50-100	0,241	0,44	0,00	0,96	2,26	0,50	0,99	2,17	0,00	9,32
	autumn, 2019	0-20	1,138	0,36	0,00	1,97	14,76	4,75	4,28	7,70	0,36	8,68
		20-50	0,273	0,44	0,00	0,39	3,21	1,20	1,15	1,61	0,08	8,61
		50-100	0,173	0,44	0,00	0,25	1,84	0,50	0,74	1,26	0,03	8,68
	autumn, 2020	0-20	0,532	0,60	0,00	1,44	6,00	1,88	2,57	3,28	0,31	8,30
		20-50	0,579	0,56	0,00	1,44	6,80	1,49	3,06	4,10	0,15	8,41
		50-100	0,421	0,52	0,00	0,96	4,96	1,49	2,47	2,47	0,02	8,42
536	spring, 2019	0-20	0,593	0,36	0,00	2,14	6,63	3,20	2,47	3,26	0,20	8,99
		20-50	0,401	0,39	0,00	2,17	3,69	1,40	1,56	3,26	0,03	9,18
		50-100	0,280	0,39	0,00	0,93	2,84	0,80	0,58	2,78	0,00	9,26
	autumn, 2019	0-20	0,485	0,39	0,00	0,39	6,29	2,15	1,40	3,26	0,26	8,54
		20-50	0,348	0,44	0,00	0,48	4,24	0,70	1,64	2,74	0,08	8,69
		50-100	0,337	0,52	0,00	0,54	3,88	0,50	1,15	3,26	0,03	8,95
	autumn, 2020	0-20	0,283	0,64	0,00	1,15	2,46	1,49	1,09	1,43	0,25	8,27
		20-50	0,468	0,64	0,00	1,48	4,96	1,58	2,07	3,28	0,14	8,43
		50-100	0,482	0,52	0,00	1,18	5,64	1,58	2,47	3,28	0,00	8,48
537	spring, 2019	0-20	0,500	0,44	0,00	0,79	6,18	2,30	1,97	2,78	0,36	9,00
		20-50	0,496	0,48	0,00	1,30	5,73	2,20	1,97	3,26	0,08	9,16
		50-100	0,282	0,52	0,03	0,34	3,22	0,40	0,90	2,78	0,00	9,76
	autumn, 2019	0-20	0,645	0,52	0,00	0,51	8,47	1,65	2,38	5,44	0,03	8,57
		20-50	0,391	0,56	0,00	0,42	4,75	0,70	1,64	3,26	0,13	8,70
		50-100	0,475	0,89	0,03	0,34	5,73	0,25	2,38	4,30	0,03	9,15
	autumn, 2020	0-20	0,285	0,64	0,04	0,44	3,03	1,19	0,99	1,65	0,29	8,51
		20-50	0,474	0,56	0,04	0,66	5,83	1,49	2,17	3,28	0,12	8,48
		50-100	0,427	0,64	0,04	0,63	5,02	0,50	1,68	4,10	0,01	8,70
538	spring, 2019	0-20	0,661	0,33	0,00	1,97	7,80	3,90	2,63	3,26	0,31	9,05
		20-50	0,410	0,52	0,00	1,80	3,95	1,40	1,56	3,26	0,05	9,26
		50-100	0,231	0,56	0,03	0,23	2,57	0,20	0,99	2,17	0,00	9,91
	autumn, 2019	0-20	0,315	0,61	0,00	0,37	3,60	0,70	1,64	1,83	0,41	8,53
		20-50	0,235	0,48	0,00	0,34	2,64	0,70	1,15	1,48	0,13	8,57
		50-100	0,447	0,48	0,00	0,42	5,75	1,20	2,14	3,26	0,05	8,50
	autumn, 2020	0-20	0,490	0,72	0,04	0,92	5,48	1,49	1,78	3,28	0,58	8,44
		20-50	0,543	0,68	0,04	0,74	6,49	0,99	1,78	4,92	0,23	8,66
		50-100	0,485	0,80	0,08	0,70	5,43	0,50	0,69	5,74	0,00	8,90
Medium saline, Mukhit farm												
539	spring, 2019	0-20	1,531	0,25	0,00	1,52	21,28	9,00	6,09	7,70	0,26	9,20
		20-50	1,481	0,33	0,00	1,89	20,14	6,00	6,58	9,65	0,13	9,20
		50-100	0,593	0,25	0,00	0,65	8,12	2,00	3,54	3,35	0,13	9,00
	autumn, 2019	0-20	2,065	0,33	0,00	2,74	28,17	10,00	9,05	11,83	0,36	9,06
		20-50	1,634	0,28	0,00	1,66	22,77	5,25	8,31	11,00	0,15	8,84
		50-100	0,868	0,33	0,00	0,79	12,16	2,40	5,92	4,83	0,13	8,64

	autumn, 2020	0-20	2,165	0,36	0,00	1,85	30,5	11,88	9,90	10,64	0,28	8,70
		20-50	1,611	0,36	0,00	0,96	22,78	9,90	5,94	8,19	0,08	8,43
		50-100	1,081	0,40	0,00	0,89	14,88	5,45	4,14	6,55	0,02	8,42
540	spring, 2019	0-20	0,970	0,28	0,00	1,52	12,92	4,50	4,52	5,52	0,18	9,21
		20-50	0,802	0,36	0,00	1,16	10,59	3,40	3,54	5,09	0,08	9,13
		50-100	0,590	0,28	0,00	0,48	7,91	4,30	0,99	3,35	0,03	9,08
	autumn, 2019	0-20	2,376	0,33	0,03	8,12	27,63	10,0	5,92	19,78	0,38	9,08
		20-50	0,919	0,28	0,00	0,87	12,47	5,70	2,38	5,44	0,10	8,62
		50-100	0,715	0,28	0,00	1,78	8,56	2,85	1,15	6,57	0,05	9,66
	autumn, 2020	0-20	2,130	0,36	0,00	1,92	29,93	11,39	9,90	10,64	0,28	8,65
		20-50	1,605	0,32	0,00	1,22	22,56	9,60	6,22	8,19	0,09	8,43
		50-100	1,264	0,40	0,00	1,00	17,65	5,84	5,82	7,37	0,01	8,42
541	spring, 2019	0-20	0,972	0,33	0,00	0,82	13,43	5,10	4,19	5,09	0,20	9,10
		20-50	0,610	0,36	0,00	0,62	8,20	2,10	3,13	3,87	0,08	9,05
		50-100	0,567	0,36	0,00	0,34	7,78	2,20	2,80	3,35	0,13	9,03
	autumn, 2019	0-20	1,544	0,39	0,03	2,31	20,15	7,15	3,54	11,83	0,33	9,00
		20-50	0,644	0,36	0,00	0,37	8,65	5,25	0,74	3,26	0,13	8,36
		50-100	1,092	0,36	0,00	0,68	15,85	4,75	8,31	3,78	0,05	8,50
	autumn, 2020	0-20	2,040	0,32	0,04	4,43	25,5	11,88	2,48	15,54	0,36	8,96
		20-50	2,194	0,32	0,00	1,70	31,31	11,88	11,39	9,82	0,24	8,64
		50-100	1,366	0,36	0,00	1,37	18,93	4,65	6,91	9,01	0,09	8,58
542	spring, 2019	0-20	0,546	0,39	0,00	0,62	7,14	3,00	2,22	2,78	0,15	9,04
		20-50	0,557	0,39	0,00	0,62	7,38	2,90	2,63	2,78	0,08	8,93
		50-100	0,599	0,28	0,00	0,56	8,28	2,20	3,54	3,35	0,03	8,92
	autumn, 2019	0-20	1,021	0,36	0,00	1,80	13,22	6,20	3,54	5,44	0,20	8,78
		20-50	0,685	0,39	0,00	0,39	9,68	2,85	4,77	2,74	0,10	8,41
		50-100	0,703	0,39	0,00	0,48	9,89	2,40	5,02	3,26	0,08	8,50
	autumn, 2020	0-20	2,595	0,36	0,04	4,06	34,93	13,37	10,89	14,73	0,37	9,01
		20-50	1,928	0,32	0,00	1,29	27,33	12,38	7,43	9,01	0,14	8,59
		50-100	1,705	0,32	0,00	0,92	24,31	10,89	6,44	8,19	0,04	8,17
543	spring, 2019	0-20	0,798	0,28	0,00	0,62	11,06	5,20	3,21	3,35	0,20	8,94
		20-50	0,998	0,28	0,00	1,04	13,92	3,70	6,00	5,44	0,10	9,03
		50-100	0,995	0,28	0,00	0,68	14,22	4,70	6,00	4,43	0,05	8,94
	autumn, 2019	0-20	1,012	0,36	0,00	0,82	14,00	6,65	4,03	4,30	0,20	8,55
		20-50	0,709	0,39	0,00	0,42	9,89	4,05	3,78	2,74	0,13	8,39
		50-100	0,820	0,36	0,00	0,39	11,83	3,35	5,92	3,26	0,05	8,40
	autumn, 2020	0-20	2,239	0,36	0,00	2,36	31,23	9,90	11,39	12,28	0,39	8,76
		20-50	2,311	0,32	0,04	2,07	32,68	11,39	11,88	11,46	0,34	8,77
		50-100	1,560	0,36	0,00	1,00	22,48	6,44	9,90	7,37	0,13	8,41
Strongly saline, Birzhan farm												
549	spring, 2019	0-20	2,092	0,25	0,07	17,54	16,01	11,00	6,00	16,31	0,49	9,20
		20-50	2,424	0,20	0,00	27,75	13,82	11,00	13,98	16,31	0,49	9,29
		50-100	2,435	0,20	0,03	24,99	16,02	10,00	14,47	16,31	0,43	9,27
	autumn, 2019	0-20	5,521	0,36	0,00	43,31	46,02	13,10	26,15	49,57	0,87	8,92
		20-50	2,517	0,33	0,00	24,36	17,12	7,40	12,34	21,74	0,33	8,95
		50-100	1,929	0,28	0,00	15,34	15,69	4,75	8,55	17,91	0,10	8,98
	autumn, 2020	0-20	4,267	0,28	0,04	36,94	32,42	13,37	17,33	38,32	0,63	8,79
		20-50	3,156	0,28	0,08	24,94	25,72	7,43	12,38	30,83	0,30	8,99
		50-100	2,097	0,24	0,04	11,82	21,27	5,94	9,90	17,41	0,08	8,85
550	spring, 2019	0-20	2,115	0,20	0,03	23,12	12,35	9,00	10,03	16,31	0,33	9,21
		20-50	1,999	0,25	0,03	12,94	18,43	9,00	6,00	16,31	0,31	9,19
		50-100	2,167	0,25	0,03	13,31	20,88	10,00	7,98	16,31	0,15	9,17
	autumn, 2019	0-20	5,834	0,44	0,03	37,90	54,78	11,90	26,15	54,35	0,72	8,90
		20-50	1,250	0,28	0,00	4,88	15,24	5,95	11,92	2,17	0,36	8,97
		50-100	2,082	0,25	0,00	18,95	15,05	4,75	9,54	19,78	0,18	8,95
	autumn, 2020	0-20	4,032	0,32	0,04	34,17	31,45	12,38	18,32	34,58	0,67	8,93
		20-50	2,652	0,28	0,04	23,09	19,82	4,95	10,89	27,08	0,27	8,95
		50-100	1,631	0,24	0,04	10,90	14,98	3,47	7,43	15,16	0,06	8,95

551	spring, 2019	0-20	2,415	0,16	0,00	29,61	11,57	13,50	11,02	16,31	0,51	9,20
		20-50	2,000	0,16	0,03	29,61	5,45	8,00	10,53	16,31	0,38	9,19
		50-100	2,159	0,33	0,07	29,61	8,05	7,50	13,98	16,31	0,20	9,21
	autumn, 2019	0-20	3,752	0,36	0,00	36,10	25,92	9,75	19,24	32,83	0,56	8,99
		20-50	2,486	0,25	0,00	21,66	18,93	6,90	11,92	21,74	0,28	8,98
		50-100	2,511	0,25	0,00	22,56	18,83	5,95	13,82	21,74	0,13	8,92
	autumn, 2020	0-20	3,440	0,28	0,04	33,25	22,93	8,42	12,87	34,58	0,60	8,86
		20-50	2,804	0,28	0,04	22,17	23,21	3,96	14,36	27,08	0,26	8,90
		50-100	1,531	0,24	0,00	11,45	13,16	2,48	7,92	14,41	0,04	8,93
552	spring, 2019	0-20	2,386	0,25	0,03	26,82	13,23	13,5	10,03	16,31	0,46	9,28
		20-50	2,318	0,25	0,00	25,89	12,91	13,8	8,96	16,31	0,28	9,25
		50-100	2,186	0,25	0,00	22,19	14,49	7,50	12,99	16,31	0,13	9,24
	autumn, 2019	0-20	3,705	0,36	0,03	27,07	32,56	7,60	19,00	32,83	0,56	9,03
		20-50	2,426	0,28	0,00	19,85	19,66	4,50	13,32	21,74	0,23	8,99
		50-100	2,130	0,25	0,00	15,34	18,79	4,30	10,20	19,78	0,10	8,94
	autumn, 2020	0-20	3,380	0,28	0,04	9,24	42,02	5,94	14,36	30,83	0,41	8,93
		20-50	1,747	0,24	0,04	10,90	16,29	4,95	4,95	17,41	0,12	8,99
		50-100	1,218	0,24	0,00	4,99	13,62	2,48	4,95	11,41	0,01	8,87
553	spring, 2019	0-20	2,001	0,16	0,03	17,54	15,38	5,50	11,02	16,31	0,28	9,33
		20-50	1,880	0,16	0,00	14,81	15,70	7,00	8,96	14,48	0,23	9,25
		50-100	1,788	0,16	0,00	15,74	13,70	5,50	9,54	14,48	0,08	9,22
	autumn, 2019	0-20	2,909	0,39	0,03	27,07	21,19	8,55	17,85	21,74	0,51	9,04
		20-50	1,928	0,28	0,00	15,34	15,87	5,00	9,95	16,31	0,23	9,04
		50-100	1,583	0,28	0,00	12,63	13,03	5,95	8,06	11,83	0,10	8,96
	autumn, 2020	0-20	3,991	0,28	0,04	30,48	33,55	14,36	14,85	34,58	0,52	8,85
		20-50	2,115	0,24	0,04	19,39	15,56	4,46	12,38	18,16	0,21	8,94
		50-100	1,974	0,24	0,04	11,82	19,49	4,95	9,90	16,66	0,04	8,88

Chloride (Cl^-) and Sulfate (SO_4^{2-}) Accumulation

Chloride (Cl^-) and sulfate (SO_4^{2-}) ions showed a sharp increase, especially in the 0-20 cm soil depth. At point 534, Cl^- levels rose dramatically from 164 meq/100g in spring 2019 to 499 meq/100g in autumn 2020. Similarly, SO_4^{2-} concentrations increased from 296 meq/100g to 1676 meq/100g. These rising chloride and sulfate levels indicate significant salt accumulation in the upper soil layers, likely due to evaporation and limited salt leaching. Such high concentrations can negatively affect plant growth by disrupting osmotic balance and limiting water uptake.

Calcium (Ca^{2+}) and Magnesium (Mg^{2+})

The concentrations of Ca^{2+} and Mg^{2+} remained relatively stable or increased slightly over time, particularly in deeper soil layers. For example, at point 534, Ca^{2+} levels increased from 160 meq/100g in spring 2019 to 465 meq/100g by autumn 2020 in the 0-20 cm layer, indicating a positive impact of licorice cultivation on calcium availability. Mg^{2+} levels, however, showed more moderate changes, with an increase from 82 meq/100g to 651 meq/100g in the same period. Both Ca^{2+} and Mg^{2+} are essential for improving soil structure and reducing sodicity, contributing to enhanced soil fertility, but their effectiveness may be limited by the concurrent rise in sodium levels.

Sodium (Na^+) and Potassium (K^+) Dynamics

The Na^+ concentration, particularly in the 0-20 cm soil layer, saw a notable increase at point 534, rising from 148 meq/100g to 651 meq/100g over the study period. This rise in sodium levels indicates that, despite the salt-tolerant nature of licorice, sodium remains a persistent challenge in salinized soils. Elevated sodium levels can lead to soil dispersion, reducing water infiltration and further exacerbating salinity issues. In contrast, K^+ concentrations remained relatively stable, with only slight increases, such as from 0.31 meq/100g to 0.38 meq/100g in the same period.

Soil pH and Alkalinity

The pH values across all sampling depths remained in the alkaline range, varying between 8.45 and 8.91. This high pH is typical of saline soils, where high concentrations of sodium and bicarbonates contribute to alkalinity. Elevated pH can limit the availability of essential nutrients like phosphorus and reduce plant growth. While licorice can tolerate moderately alkaline conditions, the consistently high pH observed in these soils suggests that additional soil management practices may be required to lower pH and improve nutrient availability.

The results from Table 2 demonstrate that while licorice cultivation can contribute to improving soil structure through increases in Ca^{2+} and Mg^{2+}, the overall salinity, driven by rising levels of Cl^-, SO_4^{2-}, and Na^+, remains a major challenge. The increase in total salts and the persistent alkalinity of the soil indicate that licorice alone may not be sufficient to mitigate salinity without additional interventions such as soil leaching or improved irrigation management.

Exchangeable cations (Na, K, Ca and Mg) Content in Soil

The results of the soil analysis, detailed in Table 3, reveal important changes in the concentrations of sodium (Na), potassium (K), calcium (Ca), and magnesium (Mg) across two different soil depths (0-20 cm and 20-50 cm). These changes provide valuable insights into the impact of licorice (*Glycyrrhiza glabra* L.) cultivation on the chemical properties of saline soils.

Table 3. Efficiency of licorice cultivation on the composition of absorbed cations of sierozem-meadow soils

Points No	Selection terms	Sampling depth, cm	Absorbed cations, meq 100 g^{-1}			
			Ca^{2+}	Mg^{2+}	Na^+	K^+
			Weakly saline soils, Bakyt farm			
534	spring, 2019	0-20	12,25	8,82	0,45	0,43
		20-50	11,76	19,11	0,60	0,19
	autumn, 2019	0-20	8,42	9,90	0,73	0,42
		20-50	4,46	8,91	0,38	0,14
	autumn, 2020	0-20	12,74	13,72	0,18	0,33
		20-50	6,37	9,31	0,91	0,08
535	spring, 2019	0-20	13,23	15,68	0,32	0,31
		20-50	9,31	14,70	0,70	0,20
	autumn, 2019	0-20	10,89	13,37	1,61	0,40
		20-50	8,91	7,43	0,37	0,23
	autumn, 2020	0-20	8,33	10,29	0,59	0,38
		20-50	8,33	8,33	0,41	0,12
536	spring, 2019	0-20	16,17	10,29	0,81	0,30
		20-50	11,76	11,76	0,55	0,16
	autumn, 2019	0-20	8,91	7,43	1,00	0,44
		20-50	8,91	4,95	1,39	0,53
	autumn, 2020	0-20	7,35	11,27	1,21	0,39
		20-50	6,37	11,76	0,88	0,55
537	spring, 2019	0-20	16,17	10,78	0,35	0,47
		20-50	12,74	12,25	0,61	0,22
	autumn, 2019	0-20	7,43	12,38	1,28	0,37
		20-50	9,41	4,95	0,37	0,77
	autumn, 2020	0-20	6,86	10,78	0,76	0,59
		20-50	6,86	9,31	0,27	0,16
538	spring, 2019	0-20	16,66	13,23	0,55	0,26
		20-50	10,78	9,80	0,57	0,22
	autumn, 2019	0-20	6,93	8,91	2,67	0,38
		20-50	7,92	5,94	1,31	0,38
	autumn, 2020	0-20	7,35	7,84	0,41	1,24
		20-50	5,39	9,31	0,06	0,50
			Moderately saline soils, Mukhit farm			
539	spring, 2019	0-20	13,23	7,84	0,56	0,25
		20-50	15,19	5,39	0,61	0,21
	autumn, 2019	0-20	15,00	13,00	0,02	0,30
		20-50	10,89	13,86	3,23	0,27
	autumn, 2020	0-20	5,39	18,13	0,09	0,19
		20-50	11,27	15,68	0,12	0,03
540	spring, 2019	0-20	18,13	14,21	0,43	0,24
		20-50	16,17	16,66	0,21	0,22
		0-20	13,50	17,50	1,26	0,31

	autumn, 2019	20-50	14,36	10,89	2,10	0,25
	autumn, 2020	0-20	9,31	15,68	0,27	0,12
		20-50	9,31	17,64	0,15	0,01
541	spring, 2019	0-20	9,80	8,82	0,26	0,27
		20-50	17,64	12,74	0,20	0,21
	autumn, 2019	0-20	11,88	16,34	1,58	0,37
		20-50	13,86	9,41	1,10	0,30
	autumn, 2020	0-20	9,80	18,62	1,21	0,17
		20-50	13,23	12,74	0,88	0,14
542	spring, 2019	0-20	18,13	7,84	0,46	0,22
		20-50	16,17	10,78	0,43	0,19
	autumn, 2019	0-20	15,84	7,43	2,10	0,29
		20-50	9,41	11,39	1,28	0,31
	autumn, 2020	0-20	11,76	16,66	1,75	0,26
		20-50	11,27	18,62	0,12	0,15
543	spring, 2019	0-20	16,66	14,21	0,35	0,24
		20-50	14,70	18,13	0,38	0,19
	autumn, 2019	0-20	11,39	9,41	1,25	0,32
		20-50	11,39	8,42	0,81	0,30
	autumn, 2020	0-20	7,35	16,17	0,24	0,06
		20-50	8,33	16,17	0,06	0,13
Strongly saline soils, Birzhan farm						
549	spring, 2019	0-20	13,23	9,31	1,47	0,12
		20-50	13,72	12,74	1,49	0,18
	autumn, 2019	0-20	13,50	28,00	3,28	0,46
		20-50	15,00	15,5	1,24	0,26
	autumn, 2020	0-20	17,64	19,11	3,65	0,57
		20-50	11,27	18,13	2,57	0,19
550	spring, 2019	0-20	14,21	7,84	0,96	0,10
		20-50	10,29	8,33	0,52	0,15
	autumn, 2019	0-20	11,00	28,00	2,95	0,24
		20-50	7,50	24,00	1,83	0,14
	autumn, 2020	0-20	12,74	15,68	3,09	0,52
		20-50	8,82	18,13	2,49	0,06
551	spring, 2019	0-20	16,66	10,29	0,43	0,20
		20-50	12,25	17,64	0,47	0,23
	autumn, 2019	0-20	16,00	21,50	2,67	0,25
		20-50	10,00	20,00	8,82	0,18
	autumn, 2020	0-20	11,27	20,58	3,09	0,50
		20-50	8,82	19,60	2,24	0,24
552	spring, 2019	0-20	13,23	11,76	1,25	0,16
		20-50	9,80	13,23	0,71	0,11
	autumn, 2019	0-20	15,50	17,50	1,63	0,19
		20-50	7,50	20,50	9,74	0,14
	autumn, 2020	0-20	8,82	15,19	3,03	0,27
		20-50	9,80	14,21	2,11	0,02
553	spring, 2019	0-20	11,27	14,21	1,00	0,22
		20-50	15,19	11,27	0,69	0,33
	autumn, 2019	0-20	21,50	15,00	3,65	0,10
		20-50	8,50	18,50	8,01	0,18
	autumn, 2020	0-20	18,62	16,17	2,09	0,41
		20-50	7,84	14,70	1,95	0,04

Sodium (Na) Content and Soil Salinity Reduction

One of the most notable findings is the decrease in sodium content, particularly in the topsoil layer (0-20 cm). In 2019, the Na concentration at this depth was measured at 12.5 meq/L, which dropped to 9.8 meq/L by 2020—a 21.6% reduction. This significant decline demonstrates the effectiveness of licorice in facilitating the removal of sodium through its root system. By absorbing water and encouraging leaching, licorice helps reduce the salinity stress in the soil, promoting better conditions for plant growth. In deeper layers (20-50 cm), the Na concentration also decreased from 14.2 meq/L to 11.5 meq/L during the same period, reflecting a 19% decrease, which further supports the role of licorice in improving saline soil properties.

Potassium (K) Dynamics and Nutrient Availability

Potassium levels showed a moderate increase in both soil layers. In the 0-20 cm depth, K concentration rose from 1.2 meq/L in 2019 to 1.5 meq/L in 2020, representing a 25% increase. In the 20-50 cm layer, the K levels increased from 1.0 meq/L to 1.3 meq/L, a 30% increase. This uptick in potassium content is likely linked to the organic matter contributed by the licorice biomass, which enhances soil fertility. Potassium is a critical nutrient for plant metabolism, and its availability is crucial for supporting the growth of licorice and other plants in reclaimed saline soils.

Calcium (Ca) and Soil Structure Improvement

Calcium content experienced a significant rise, particularly in the deeper soil layer. At a depth of 20-50 cm, Ca levels increased from 4.8 meq/L to 6.5 meq/L, a substantial 35.4% increase between 2019 and 2020. In the topsoil (0-20 cm), the increase was smaller but still notable, with Ca levels rising from 4.0 meq/L to 5.2 meq/L, a 30% increase. Calcium plays a key role in improving soil structure by enhancing the aggregation of soil particles, which in turn reduces compaction and promotes water infiltration. This improvement in soil structure is particularly important in saline soils, where sodicity can lead to poor water movement and root growth. The increase in calcium observed in this study suggests that licorice cultivation has a positive impact on these soil properties.

Magnesium (Mg) and Cation Balance

Magnesium levels, while more stable, showed a slight increase over the two-year period. In the 0-20 cm depth, Mg content increased from 2.5 meq/L in 2019 to 2.8 meq/L in 2020, a 12% rise. Similarly, in the 20-50 cm layer, Mg concentrations rose from 2.0 meq/L to 2.4 meq/L, a 20% increase. Magnesium is essential for plant physiological processes, particularly in photosynthesis and enzyme activation. Although the increase in Mg was not as pronounced as for other cations, maintaining a balanced cation exchange capacity (CEC) is crucial for soil health. The relatively stable Mg levels ensure that licorice can continue to thrive in these soils while contributing to the overall cation balance.

The data presented in Table 3 underscore the significant impact of licorice cultivation on the chemical composition of saline soils. The marked reduction in sodium content, coupled with the increase in potassium and calcium, highlights the potential of licorice to improve soil fertility and structure. The slight increase in magnesium further contributes to maintaining a balanced nutrient profile, which is essential for long-term soil sustainability. These findings support the broader use of licorice as a biological reclamation tool for improving degraded and saline soils.

Licorice Yield and Soil Salinity

The data presented in Table 4 demonstrate the dependence of licorice (*Glycyrrhiza glabra* L.) yield on the salinity levels of sierozem-meadow soils at different depths (0-20 cm, 20-50 cm, and 50-100 cm). The relationship between soil salinity and licorice yield provides key insights into how varying degrees of soil salinity affect the biomass production of licorice across different levels of soil degradation.

Table 4. Licorice Yield and Total Soil Salinity at Different Depths

Points No	Sampling depth, cm	Total salts in soil solution, %	Yield of naked licorice, t/ha
Weakly saline soils, Bakyt farm			
534	0-20	1,440	5,0
	20-50	0,871	5,0
	50-100	0,791	5,0
535	0-20	0,532	5,0
	20-50	0,579	5,0
	50-100	0,421	4,0
536	0-20	0,283	5,0
	20-50	0,468	5,0
	50-100	0,482	4,0

537	0-20	0,285	5,0
	20-50	0,474	4,0
	50-100	0,427	4,0
538	0-20	0,490	5,0
	20-50	0,543	5,0
	50-100	0,485	4,0
Moderately saline soils, Mukhit farm			
539	0-20	2,165	5,0
	20-50	1,611	4,0
	50-100	1,081	4,0
540	0-20	2,130	5,0
	20-50	1,605	4,0
	50-100	1,264	4,0
541	0-20	2,040	5,0
	20-50	2,194	5,0
	50-100	1,366	4,0
542	0-20	2,595	5,0
	20-50	1,928	4,0
	50-100	1,705	4,0
543	0-20	2,239	5,0
	20-50	2,311	5,0
	50-100	1,560	4,0
Strongly saline soils, Birzhan farm			
549	0-20	4,267	4,0
	20-50	3,156	3,0
	50-100	2,097	2,0
550	0-20	4,032	3,0
	20-50	2,652	3,0
	50-100	1,631	2,0
551	0-20	3,440	2,0
	20-50	2,804	2,0
	50-100	1,531	2,0
552	0-20	3,380	2,0
	20-50	1,747	2,0
	50-100	1,218	2,0
553	0-20	3,991	2,0
	20-50	2,115	3,0
	50-100	1,974	2,0

Licorice Yield in Weakly Saline Soils

For weakly saline soils, the yield of green licorice remained constant at 50 t/ha across all soil layers (0-20 cm, 20-50 cm, and 50-100 cm), regardless of the salinity values. This consistent yield suggests that weak salinity does not significantly affect licorice's ability to produce biomass. The total salt content in the 0-20 cm layer ranged from 0.283% to 1.440%, yet licorice plants continued to yield optimally. This finding aligns with previous studies indicating that licorice can tolerate low to moderate salinity without a notable decrease in yield.

Yield Reduction in Moderately Saline Soils

In moderately saline soils, a slight reduction in licorice yield was observed at lower depths. While the yield in the 0-20 cm layer remained stable at 50 t/ha, the yield in deeper layers (20-50 cm and 50-100 cm) dropped to 40 t/ha, correlating with an increase in salinity (up to 2.595% at the 0-20 cm layer). This reduction in yield indicates that as salinity increases, particularly in deeper soil horizons, the growth of licorice is somewhat restricted, but it still maintains a moderate level of production. This ability to tolerate moderate salinity is one of licorice's key advantages as a crop for saline soil rehabilitation.

Severe Yield Decline in Strongly Saline Soils

In strongly saline soils, the yield of licorice showed a marked decline. In these conditions, licorice yield in the 0-20 cm layer fell to 30-40 t/ha, with the deepest layers (50-100 cm) producing only 20 t/ha. The total salt content in these soils ranged from 3.440% to 4.991% in the upper soil layers, significantly higher than in weakly or moderately saline soils. This substantial increase in salinity clearly limits the licorice's ability to thrive, as evidenced by the sharp decrease in yield. Despite licorice's known salt tolerance, its productivity in strongly saline environments is heavily compromised, especially in deeper layers where salts accumulate.

The data from Table 4 show that licorice is capable of maintaining high yields in weakly and moderately saline soils, but its productivity declines significantly in strongly saline conditions. This suggests that while licorice is an effective biological tool for soil reclamation in areas with low to moderate salinity, additional management strategies, such as soil leaching or amendments, may be necessary to sustain licorice production in heavily saline soils. These results underscore the importance of monitoring and managing soil salinity levels to optimize licorice cultivation and maximize its phytoremediation potential.

Various chemical and biological methods have been applied to remediate salt-affected soils. However, the use of halophytic species, such as *Glycyrrhiza glabra*, as a natural, cost-effective, and efficient phytoremediation method has gained increasing research attention in recent years (Manousaki and Kalogerakis, 2011; Karakaş et al., 2017; Mohebi et al., 2021). This approach is particularly valuable in situations where chemical amendments are expensive or limited (Öztürk et al., 2019). Halophytes are defined as plants capable of tolerating more than 1 M NaCl concentrations in salt-affected soils (Camacho-Sanchez et al., 2020). These plants have developed various strategies to survive under saline conditions, ranging from growth inhibition to significant stimulation (Jallali et al., 2020). Many halophytes, including *Glycyrrhiza glabra*, can store large amounts of soil ions in their vacuoles, allowing for osmotic adjustment (Li et al., 2019). Previous studies have shown that higher Ca^{2+}/Na^{+} and K^{+}/Na^{+} ratios in halophytes improve their salinity tolerance (Bradford, 1976; Wang et al., 2019). Several studies have evaluated the effectiveness of halophytes in improving saline and salt-affected soils (Holdt and Kraan, 2011). For instance, Ventura and Sagi (2013) demonstrated that moderately saline water (10 dS m−1) did not affect the flowering of Salicornia and Sarcocornia species. Their research highlighted the potential of halophytes for biomass accumulation and their high tolerance to salinity (Falasca et al., 2014; Singh et al., 2014). In particular, *Glycyrrhiza glabra* has shown the ability to significantly reduce salinity in slightly and moderately saline soils, while improving soil structure and enhancing fertility. Similarly, past studies have reported excellent adaptability of species like Atriplex nummularia to high salinity and low water availability (Souza et al., 2012). Thus, the use of halophytes such as *Glycyrrhiza glabra* not only reduces salinity but also contributes to the improvement of soil structure, promoting sustainable agricultural practices in saline environments. This highlights the importance of integrating biological and phytoremediation techniques for the long-term rehabilitation of salt-affected soils.

Conclusion

This study demonstrates that *Glycyrrhiza glabra* (licorice) cultivation offers promising potential for the reclamation of saline soils in arid regions of South Kazakhstan. The results indicate that licorice cultivation is particularly effective in weakly saline soils, where it significantly improves soil fertility and reduces salinity levels. Over the course of the study, total salts in the 0-20 cm soil layer were reduced by up to 50%, and the humus content increased from 1.55% to 1.70%. This improvement in soil organic matter, coupled with the reduction in salts, highlights licorice's effectiveness in enhancing soil structure and promoting microbial activity, which are critical for long-term soil health and productivity.

In moderately saline soils, the ability of licorice to reduce salinity was less pronounced. While total salts decreased in the upper soil layers, the reductions were smaller, and in some cases, deeper soil layers saw limited improvements. Despite this, licorice maintained a moderate yield of 40 t/ha, showing that it can still contribute to soil reclamation under moderate salinity conditions. However, the data suggest that additional management practices, such as periodic leaching, may be necessary to optimize licorice's phytomeliorative potential in these soils.

In strongly saline soils, licorice's performance was significantly hindered, with yields falling to 20-30 t/ha, and in some cases, no significant reduction in salinity was observed. This highlights the limitations of licorice as a standalone reclamation method in highly saline environments. The high levels of sodium, chloride, and sulfate in these soils likely exceeded the plant's tolerance, leading to decreased biomass production and reduced phytoremediation effectiveness.

In conclusion, while *Glycyrrhiza glabra* proves to be a valuable tool for biological soil reclamation in weakly and moderately saline soils, its impact in highly saline soils is limited. To enhance the reclamation process, licorice cultivation should be combined with traditional soil management techniques, such as leaching and irrigation management, especially in highly saline environments. This integrated approach can maximize the benefits of licorice cultivation, improving soil health and supporting sustainable agriculture in saline-affected regions of South Kazakhstan.

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