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GEOCHEMICAL CHARACTERISTICS OF SALINE SOILS IN THE ATYRAU REGION AS A BASIS FOR THE USE OF KOCHIA PROSTRATA FOR PHYTOMELIORATION

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Abstract. *Relevance*. Soil salinization in the Caspian Lowland is a major exogenous geological process affecting the geochemical state of landscapes in the Atyrau region. Controlled by lithology, groundwater mineralization, and arid climatic conditions, it governs the migration and accumulation of chemical elements and contributes to soil degradation in the northern desert zone. *The objective* This study aimed to characterize the geochemistry of saline soils in the Atyrau region by assessing the vertical distribution of soluble salts, exchangeable cations, organic matter, and particle-size composition. *Methods.* A layer-by-layer study was carried out on soil profile P-1 to a depth of 200 cm. The composition of the aqueous extract, the qualitative composition of salts, the content of absorbed bases (according to Kappen), humus (according to Tyurin), mobile forms of phosphorus and potassium (according to Machigin), nitrates, the pH value (using the potentiometric method) and the particle size distribution (according to Kachinsky) were determined. *Results*. Readily soluble salts increased from 0.196-0.293% in the 0-40 cm layer to 7.864% at 80-100 cm depth. The soils exhibited sulfate-chloride sodium salinization (Cl^-/SO_4^{2-} = 1.5-2.4; $Na^+/(Ca^{2+}+Mg^{2+})$ = 3.0-12.9) with no soda salinization (pH 7.18-7.83). The proportion of toxic salts is 80.2-95.8%, and the content of exchangeable sodium in the soil-absorbing complex reaches 26.5-40.1%, which corresponds to highly solonetzic soils. The soils were heavy loamy to light clayey, with 46.7-80.2% physical clay and low humus content (0.70-1.45%). *Conclusion*. The study provides the first comprehensive layer-by-layer geochemical characterization of saline soils in the northern desert subzone of the Atyrau region. The results reveal vertical patterns of salt, exchangeable cation, organic matter, and particle-size distribution, providing a scientific basis for the geoecological assessment, monitoring, and sustainable management of saline lands.

Keywords: saline soils, salt profile, exchangeable sodium, solonetzicity, phytomelioration, *Kochia prostrata*, Atyrau region, land degradation

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АТЫРАУ ОБЛЫСЫНДАҒЫ ТҰЗДЫ ТОПЫРАҚТАРДЫҢ ГЕОХИМИЯЛЫҚ СИПАТТАМАЛАРЫ ФИТОМЕЛИОРАЦИЯ ҮШІН KOCHIA PROSTRATA ПАЙДАЛАНУ НЕГІЗІ РЕТІНДЕ

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Аннотация. *Өзектілігі.* Каспий ойпатындағы топырақтың тұздануы - Атырау облысы ландшафттарының геохимиялық жағдайын анықтайтын қазіргі заманғы экзогендік геологиялық процестердің ең тән көріністерінің бірі. Тұздың жиналуы аумақтың литологиялық құрылымының ерекшеліктерімен, жер асты суларының минералдануымен, құрғақ климаттық жағдайлармен және жоғары буланумен байланысты. Тұзды топырақтардың геохимиялық сипаттамаларын кешенді зерттеу химиялық элементтердің миграциясы мен жиналу заңдылықтарын бағалауға, сондай-ақ солтүстік шөл аймағындағы топырақтың деградация дәрежесін анықтауға мүмкіндік береді. *Зерттеудің объектісі* - Атырау облысындағы тұзды топырақтардың кешенді геохимиялық сипаттамасын жүргізу, топырақ профилі бойынша оңай еритін тұздардың, алмасатын катиондардың, органикалық заттардың және бөлшектер мөлшерінің таралуын анықтау және тұздану процестерінің негізгі заңдылықтарын белгілеу. *Әдістер.* Р-1 топырақ профилінде 200 см тереңдікке дейін қабат-қабат зерттеу жүргізілді. Сулы сығындының құрамы, тұздардың сапалық құрамы, сіңірілген негіздердің мөлшері (Каппен бойынша), гумустың мөлшері (Тюрин бойынша), фосфор мен калийдің жылжымалы түрлері (Мачигин бойынша), нитраттардың мөлшері, pH мәні (потенциометриялық әдісті қолдану арқылы) және бөлшектердің мөлшерінің таралуы (Качинский бойынша) анықталды. *Нәтижелер*. Оңай еритін тұздардың мөлшері 0-40 см қабатта 0,196-0,293%-дан 80-100 см тереңдікте 7,864%-ға дейін артатыны анықталды. Химиялық құрамы бойынша зерттелген топырақтар тұзданудың сульфат-хлоридті натрий түріне жатады (Cl^-/SO_4^{2-} = 1,5-2,4; $Na^+/(Ca^{2+}+Mg^{2+})$ = 3,0-12,9). Сода тұздану белгілері жоқ (CO_3^{2-} - іздері, pH 7,18-7,83). Уытты тұздардың үлесі 80,2-95,8% құрайды, ал топырақ сіңіргіш кешендегі алмасатын натрий мөлшері 26,5-40,1%-ға жетеді, бұл жоғары сортаң топырақтарға сәйкес келеді. Бөлшектердің мөлшерінің таралуы бойынша топырақтар ауыр сазды және жеңіл сазды болып жіктеледі, физикалық саз мөлшері 46,7-80,2%, ал гумус мөлшері 0,70-1,45% құрайды. *Қорытынды*. Жүргізілген зерттеулер алғаш рет Атырау облысының солтүстік шөлді субзонының тұзды топырақтарының кешенді қабат-қабат геохимиялық сипаттамасын жүргізуге мүмкіндік берді. Каспий ойпатының құрғақ климатында химиялық элементтердің миграциясы мен жиналу процестерінің ерекшеліктерін көрсететін тұздардың, алмасатын катиондардың, органикалық заттардың және бөлшектердің мөлшерінің таралуының тік таралу заңдылықтары анықталды. Алынған нәтижелер тұзды аймақтарды геоэкологиялық бағалау, деградация процестерін бақылау және аймақтағы жер ресурстарын ұтымды пайдалану шараларын әзірлеу үшін ғылыми негіз бола алады.

Түйін сөздер: тұзданған топырақтар, тұз профилі, сіңірілген натрий, сортаңдану, фитомелиорация, *Kochia prostrata*, Атырау облысы, жердің тозуы

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ГЕОХИМИЧЕСКАЯ ХАРАКТЕРИСТИКА ЗАСОЛЁННЫХ ПОЧВ АТЫРАУСКОЙ ОБЛАСТИ КАК ОСНОВА ПРИМЕНЕНИЯ KOCHIA PROSTRATA ДЛЯ ФИТОМЕЛИОРАЦИИ

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Аннотация. *Актуальность.* Засоление почв Прикаспийской низменности является одним из наиболее характерных проявлений современных экзогенных геологических процессов, определяющих геохимическое состояние ландшафтов Атырауской области. Накопление солей обусловлено особенностями литологического строения территории, минерализацией грунтовых вод, аридными климатическими условиями и высокой испаряемостью. Комплексное изучение геохимических особенностей засолённых почв позволяет оценить закономерности миграции и аккумуляции химических элементов, определить степень деградации почвенного покрова северной пустынной зоны и обосновать возможность применения солеустойчивых растений в целях фитомелиорации. *Цель.* Выполнить комплексную геохимическую характеристику засолённых почв Атырауской области, определить особенности распределения легкорастворимых солей, обменных катионов, органического вещества и гранулометрического состава по почвенному профилю, а также оценить полученные показатели как основу для применения Kochia prostrata в фитомелиорации деградированных земель. *Методы.* В почвенном разрезе Р-1 проведено послойное исследование до глубины 200 см. Определены состав водной вытяжки, качественный состав солей, содержание поглощённых оснований по методу Каппена, гумуса по методу Тюрина, подвижных форм фосфора и калия по методу Мачигина, нитратов, значение pH потенциометрическим методом и гранулометрический состав по методу Качинского. *Результаты*. Установлено, что содержание легкорастворимых солей возрастает от 0,196–0,293 % в слое 0–40 см до 7,864 % на глубине 80–100 см. По химическому составу исследуемые почвы относятся к сульфатно-хлоридному натриевому типу засоления: отношение Cl^-/SO_4^{2-} составляет 1,5–2,4, а $Na^+/(Ca^{2+} + Mg^{2+})$ — 3,0–12,9. Признаки содового засоления отсутствуют: CO_3^{2-} выявлен в следовых количествах, а значение pH варьирует от 7,18 до 7,83. Доля токсичных солей составляет 80,2–95,8 %, содержание обменного натрия в почвенно-поглощающем комплексе достигает 26,5–40,1 %, что соответствует сильной степени солонцеватости. По гранулометрическому составу почвы относятся к тяжелосуглинистым и легкоглинистым; содержание физической глины составляет 46,7–80,2 %, а гумуса — 0,70–1,45 %. *Выводы.* Проведённые исследования позволили выполнить комплексную послойную геохимическую характеристику засолённых почв северной пустынной подзоны Атырауской области. Выявлены закономерности вертикального распределения солей, обменных катионов, органического вещества и гранулометрических фракций, отражающие особенности миграции и аккумуляции химических элементов в условиях аридного климата Прикаспийской низменности. Высокое содержание легкорастворимых и токсичных солей, значительная доля обменного натрия и тяжёлый гранулометрический состав подтверждают выраженную деградацию исследуемых почв. Полученные данные могут служить научной основой для геоэкологической оценки засолённых территорий, мониторинга деградационных процессов и разработки мероприятий по фитомелиорации с использованием солеустойчивых растений, включая Kochia prostrata.

Ключевые слова: засолённые почвы, солевой профиль, поглощённый натрий, солонцеватость, фитомелиорация, *Kochia prostrata*, Атырауская область, деградация земель

Introduction. Soil salinization is one of the most pervasive forms of land degradation in arid and semi-arid regions worldwide, affecting approximately 20% of irrigated agricultural land and extensive areas of natural rangelands (Flowers & Colmer, 2008). Salinity reduces soil fertility, limits vegetation productivity, and accelerates ecosystem degradation, thereby posing a major constraint to sustainable land management. This issue is particularly relevant in the Republic of Kazakhstan, where more than two-thirds of the territory is occupied by deserts and semi-deserts and the extent of degraded rangelands continues to expand under increasing climatic and anthropogenic pressures (Kaldybaev et al., 2022; Akhmedenov et al., 2025).

The Atyrau Region, situated within the Caspian Lowland, represents one of the most severely affected areas. The regional environment is characterized by an extremely arid climate, with annual precipitation of only 150-180 mm and potential evaporation exceeding precipitation by five- to seven-fold. These climatic conditions, together with shallow mineralized groundwater, fine-textured parent materials, and residual marine salinity, promote the accumulation of readily soluble salts throughout the soil profile and the widespread development of saline and solonchak soils (Mukhambetov et al., 2023; Mukhambetov et al., 2026). Intensive grazing, particularly around settlements and watering points, further exacerbates land degradation by reducing vegetation cover, increasing soil exposure, and enhancing secondary salinization and wind erosion (Akhmedenov et al., 2025).

Conventional reclamation techniques, including gypsum application and salt leaching, are of limited applicability under these conditions because of the scarcity of freshwater resources and the high economic costs associated with large-scale implementation. Consequently, phytomelioration has emerged as a more sustainable and economically feasible approach for the rehabilitation of saline rangelands. This strategy relies on the establishment of salt-tolerant perennial forage species capable of improving soil conditions while simultaneously restoring pasture productivity (Shamsutdinov et al., 2000; Kamalov, 1995). Among the species recommended for the Northern Caspian region, Kochia prostrata (L.) Schrad. (syn. Bassia prostrata (L.) A.J. Scott) is considered one of the most promising owing to its exceptional tolerance to drought and salinity, high forage value, and adaptability to arid environments (Waldron et al., 2020; Sagers et al., 2017).

Nevertheless, practical experience demonstrates that the effectiveness of phytomelioration depends not only on the ecological characteristics of the selected species but also on the degree of correspondence between plant requirements and the geochemical properties of the soil profile. Parameters such as the depth and thickness of saline horizons, salinity type and intensity, exchangeable sodium content, and particle-size distribution strongly influence root development, water availability, and plant establishment. Failure to account for these site-specific soil characteristics has resulted in unsuccessful revegetation projects, including the large-scale mortality of K. prostrata plantations established on approximately 22,400 ha in the former Guryev (present-day Atyrau) Region during 1980-1986 (Mukhambetov et al., 2026). Similar soil-related constraints have also been identified as the primary cause of the dwarf growth syndrome observed in K. prostrata populations on saline soils of the Northern Caspian region.

Despite the recognized importance of soil conditions for successful phytomelioration, detailed information on the vertical geochemical characteristics of saline soils in the northern desert subzone of the Caspian Lowland remains limited. In particular, the relationships among the vertical distribution of soluble salts, exchangeable sodium, and the suitability of these soils for *Kochia prostrata* establishment have not been comprehensively evaluated. Therefore, the objectives of this study were to provide a comprehensive geochemical characterization of a representative saline soil profile in the Atyrau Region and to establish a scientific basis for the use of *Kochia prostrata* in the phytomelioration of degraded saline rangelands. Specifically, the study aimed to: (i) determine the composition, vertical distribution, type, and degree of soil salinity; (ii) assess the composition of the soil adsorption complex and the degree of sodicity; (iii) characterize soil fertility through analyses of humus content, available nutrients, and particle-size distribution; and (iv) compare the measured soil properties with experimentally established salinity tolerance thresholds for *K. prostrata* in order to develop agronomically sound recommendations for its establishment under the saline conditions of western Kazakhstan.

Literature review. The physiological mechanisms underlying salt tolerance in halophytes have been extensively investigated (Flowers & Colmer, 2008). Halophytes are generally defined as plant species capable of completing their life cycle under salinity levels equivalent to at least 200 mmol L^{-1} NaCl. Depending on their adaptive strategy, halophytes are classified as salt accumulators or salt excluders. In salt-accumulating species, tolerance is primarily achieved through osmotic adjustment by compartmentalizing Na^+ and Cl^- ions within vacuoles while maintaining high cytosolic K^+ concentrations, thereby preserving metabolic activity.ge

Kochia prostrata is widely recognized as a facultative halophyte with high tolerance to both salinity and drought. Controlled-environment experiments demonstrated that its optimum growth occurs at approximately 150 mmol L^{-1} NaCl, accompanied by a nearly linear increase in sodium accumulation in shoot tissues (Karimi et al., 2005). Comparative studies by Sagers et al. (2017) showed that the GR_{50} (the salinity causing a 50% reduction in biomass production) ranged from 130 to 189 mmol L^{-1} NaCl for the cultivars 'Snowstorm' and 'Immigrant', respectively. Although these values are lower than those reported for highly specialized halophytes such as Atriplex gardneri and Halogeton glomeratus, K. prostrata remained viable even at 600 mmol L^{-1} NaCl (approximately 60 dS m^{-1}), indicating exceptional physiological tolerance. These findings are consistent with field observations reported by Francois (1976), who demonstrated that the species can maintain economically valuable forage production at soil salinity levels of up to approximately 17 dS m^{-1} (ECe).

An important characteristic of K. prostrata is its predominantly passive pattern of salt accumulation. The concentrations of NaCl and KCl in shoot dry matter increase almost linearly with external salinity, reaching approximately 19% at 600 mmol L^{-1} NaCl, compared with 26.9% in Atriplex gardneri (Waldron et al., 2020). This physiological trait has important implications for phytomelioration. Harvesting aboveground biomass contributes to the gradual removal of soluble salts from the site, whereas excessive salt accumulation in forage biomass may reduce its nutritional quality by increasing ash content and decreasing crude protein concentration.

The broad ecological adaptability of K. prostrata is also associated with considerable intraspecific genetic variability. Shuyskaya et al. (2022) demonstrated that the genetic diversity of natural populations is closely related to soil environmental conditions, while subsequent research showed that the development of adaptive responses in this C_4 halophyte depends on both the intensity and duration of salt exposure. Furthermore, breeding studies involving introgressive hybrids have demonstrated the potential for enhancing salinity tolerance through targeted genetic improvement (Meldebekova et al., 2023).

Despite substantial progress in understanding the physiological and genetic mechanisms of salt tolerance in K. prostrata, considerably less attention has been paid to the edaphic conditions governing its successful establishment under field conditions. In particular, quantitative relationships between soil profile characteristics–including the vertical distribution of soluble salts, sodicity, and soil texture–and the performance of K. prostrata in the saline rangelands of the Caspian Lowland remain insufficiently documented. Addressing this knowledge gap is essential for developing scientifically sound phytomelioration strategies in western Kazakhstan.

The phytomeliorative potential of cypress in post-irrigation and degraded lands of Central Asia was considered by Sh. Kamalov (1995) in relation to the Aral Sea region. For Western Kazakhstan, B. Mukhambetov et al. (2026) found that northern desert soils are almost universally highly saline from a depth of 40-60 cm and that the highest productivity of K. prostrata (2.74 t/ha of "fruit feed" and 2.84 t/ha of pasture mass) is achieved with winter (January) sowing on snow, which ensures natural cold stratification of the seeds.

Thus, extensive data has been accumulated on both the salt tolerance of K. prostrata and the agricultural practices for its cultivation. However, a comparison of the quantitative thresholds of salt tolerance of the species with the layer-by-layer geochemical characteristics of specific soils of the Atyrau region has not been carried out previously, which determined the objectives of this study.

Materials and Methods. The study involved saline soils of the northern desert subzone of the Atyrau region (section P-1), established as part of a study on the phytomeliorative effectiveness of prostrate cypress. The soil section was opened to a depth of 200 cm; samples were collected layer by layer: every 10 cm in the 0-60 cm layer and every 20 cm in the 60-200 cm layer (a total of 13 horizons). Samples of the root zone (0-60 and 0-50 cm, respectively) were used to determine the soil conversion complex (UCC), humus, and mobile nutrient content. Each horizon was a composite sample composed of individual samples using the envelope method; analytical determinations were repeated three times. Laboratory tests were performed in an accredited laboratory using standardized methods:

– chemical composition of the aqueous extract (soil: water ratio = 1:5) - determination of CO_3^{2-} and HCO_3^- by titrimetry, Cl^- - by Mohr's argentometric method, SO_4^{2-} - by gravimetry, Ca^{2+} and Mg^{2+} - complexometrically, the sum of Na^++K^+ - by the difference between the sum of anions and the sum of divalent cations;

– the sum of absorbed bases and the composition of exchangeable cations (Ca^{2+}, Mg^{2+}, Na^+) - by the Kappen method;

– organic matter (humus) content - by the Tyurin method;

– mobile forms of phosphorus and potassium - by the Machigin method in an ammonium carbon extract; - Nitrates - spectrometric;

– pH of the aqueous extract - potentiometric;

– Particle size distribution - N.A. Kachinsky's pipette method, classifying varieties by physical clay content (particles <0.01 mm).

The qualitative composition of salts was calculated using the "hypothetical salts" method, dividing them into non-toxic ($Ca(HCO_3)_2$, $CaSO_4$) and toxic ($NaHCO_3$, $MgSO_4$, Na_2SO_4, $MgCl_2$, $NaCl$) compounds. The degree and chemistry of salinization were assessed based on the solid residue content and the Cl^-/SO_4^{2-} anion ratio in mg-eq (Mirdadayev M., and et al., 2022). The degree of solonetzic soil salinity was determined based on the exchangeable sodium percentage of total absorbed bases (ESP), as well as the calculated sodium adsorption rate ($SAR = Na^+/\sqrt{[(Ca^{2+}+Mg^{2+})/2]}$.

To compare the obtained data with the results of international pot experiments, where salt tolerance is expressed in electrical conductivity units, an approximate conversion of salt content to ECe was performed using a conversion factor of 15 dS/m per 1% salt content, adopted for chloride and sulfate-chloride salinity types. ECe values should be considered estimates and used only for qualitative comparison with published threshold values.

Statistical data processing was performed using descriptive statistics and correlation analysis (Pearson's linear correlation coefficient, r). The reliability of the analytical data was monitored using the anion and cation balance of the aqueous extract: the discrepancy between the sums did not exceed 1.5 mg-eq/100 g (0.4% on average), confirming the accuracy of the determinations. Graphical processing of the results was performed in Python (Matplotlib library).

Results and discussion. Salt profile and type of salinization. The results of the water extract analysis (Table 1) indicate a pronounced differentiation of the soil profile in terms of the content of readily soluble salts. In the 0-40 cm layer, the total salt content varies within a narrow range of 0.196-0.293%, which corresponds to a low degree of salinization. Starting from a depth of 40 cm, an avalanche-like increase in the salt background occurs: 0.844% (40-50 cm), 2.650% (50-60 cm), 4.776% (60-80 cm), with an absolute maximum of 7.864% at a depth of 80-100 cm. Below 100 cm, the salt content remains consistently high (4.247-7.385%), forming a powerful solonchak horizon.

Table 1. Chemical composition of the aqueous extract of soils from section P-1 (numerator - % of absolutely dry soil, denominator - mg-eq/100 g).

Horizon, cm	Total salts, %	CO_3^{2-}	HCO_3^-	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	Na^++K^+	pH
0-10	0,196	Not detected	0,059 0,97	0,048 1,35	0,027 0,56	0,008 0,40	0,004 0,33	0,050 2,17	7,65
10-20	0,293	Not detected	0,059 0,97	0,075 2,11	0,063 1,31	0,006 0,30	0,005 0,42	0,085 3,70	7,80
20-30	0,246	Not detected	0,061 1,00	0,061 1,72	0,044 0,92	0,006 0,30	0,004 0,33	0,070 3,04	7,83
30-40	0,208	Not detected	0,056 0,92	0,052 1,46	0,033 0,69	0,006 0,30	0,004 0,33	0,057 2,48	7,75
40-50	0,844	Not detected	0,039 0,64	0,291 8,20	0,221 4,60	0,024 1,20	0,013 1,08	0,256 11,13	7,50
50-60	2,650	Not detected	0,041 0,67	0,890 25,07	0,782 16,29	0,070 3,50	0,022 1,83	0,845 36,74	7,25
60-80	4,776	Not detected	0,037 0,61	1,945 54,79	1,094 22,79	0,270 13,50	0,066 5,50	1,364 59,30	7,18
80-100	7,864	Not detected	0,044 0,72	2,893 81,49	2,126 44,29	0,218 10,90	0,089 7,42	2,494 108,43	7,30
100-120	5,810	Not detected	0,051 0,84	2,308 65,01	1,382 28,79	0,176 8,80	0,084 7,00	1,809 78,65	7,35
120-140	5,812	Not detected	0,051 0,84	2,325 65,49	1,368 28,50	0,164 8,20	0,084 7,00	1,820 79,13	7,41
140-160	4,247	Not detected	0,046 0,75	1,509 42,51	1,176 24,50	0,050 2,50	0,028 2,33	1,438 62,52	7,55

160-180	7,385	Not detected	0,056 0,92	2,609 73,49	2,088 43,50	0,092 4,60	0,049 4,08	2,491 108,30	7,37
180-200	6,489	Not detected	0,059 0,97	2,361 66,51	1,752 36,50	0,118 5,90	0,033 2,75	2,166 /94,17	7,42

Note - $Na^{+}+K^{+}$ determined by difference; abc - not detected.

The salinity chemistry remains uniform throughout the profile. The Cl^{-}/SO_4^{2-} ratio in mg-eq varies from 1.54 to 2.41, corresponding to the sulfate-chloride (and in places, chloride) type of salinity. Sodium is absolutely dominant in the cation composition: the $Na^{+}/(Ca^{2+}+Mg^{2+})$ ratio increases from 3.0-5.1 in the upper horizons to 10.9-12.9 in the 140-200 cm layer. Therefore, salinity is classified as sodium sulfate-chloride. Carbonate ion was not detected in any horizon, and the pH value is in the range of 7.18-7.83, meaning soda (alkaline) salinity, which is most dangerous for plants and difficult to reclaim, is absent. A significant negative correlation is observed between pH and total salt concentration ($r = -0.75$), due to the diluting effect of neutral sodium salts. The Cl^{-}, SO_4^{2-}, and $Na^{+}+K^{+}$ concentrations are practically functionally related to total salt concentration ($r = 0.996$; 0.993, and 0.997, respectively), indicating a common source of salt accumulation: mineralized groundwater and residual sea salts.

The distribution of ions across the profile is clearly illustrated in Figure 1, where anions are plotted to the left and cations to the right of the zero axis. It is clearly visible that the upper part of the profile (0-35 cm) is virtually devoid of salts, while in the 40-100 cm range, a "core" of the salt maximum forms, represented primarily by sodium chlorides and sulfates.

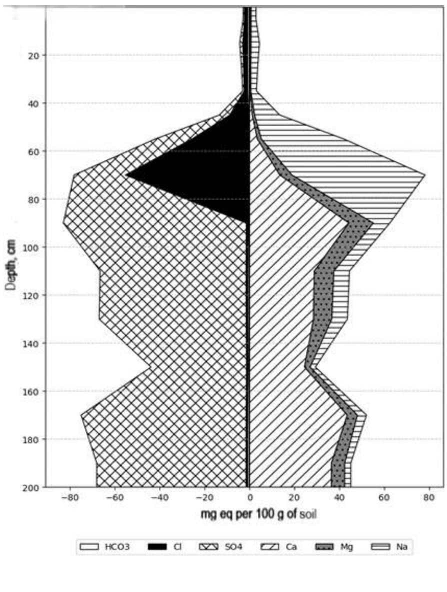

Figure 1. Profile of the salt composition of soils (section P-1): anions (to the left) and cations (to the right) from the zero axis, mg-eq per 100 g of soil.

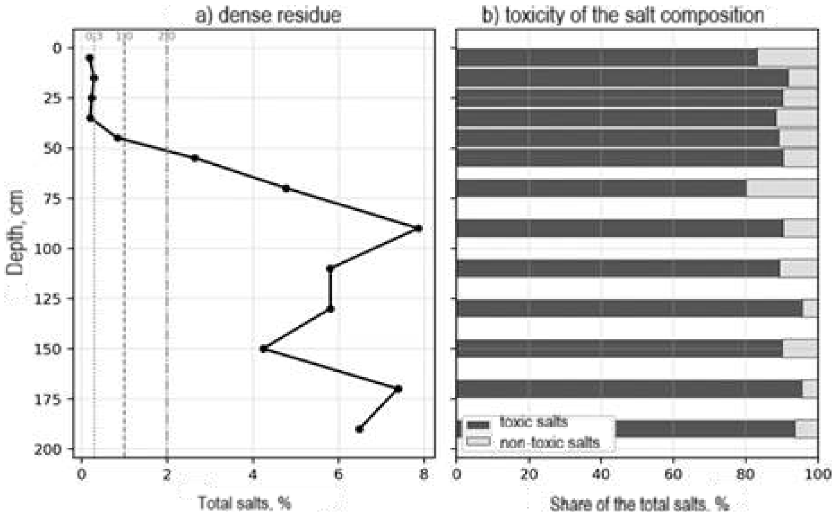

Figure 2. Distribution of the sum of easily soluble salts (a) and the ratio of toxic and non-toxic salts (b) along the profile of section P-1.

According to the salinity gradations for chloride and sulfate-chloride chemistry (Figure 2, a), soils in the 0-40 cm layer are classified as slightly saline (0.2-0.4%), the 40-50 cm horizon as highly saline (0.6-1.0%), and all underlying horizons (more than 2%) as solonchakous. According to the classification, the soil under study can be defined as a brown desert solonchakous heavy loam soil with a solonchakous horizon below 50-60 cm.

Qualitative composition of salts and their toxicity. Calculation of the hypothetical salt composition (Table 2, Figure 3) showed that the proportion of toxic compounds in all horizons is extremely high, amounting to 80.24-95.77% of the total salts. The leading salt is sodium chloride, the content of which increases from 31.63% in the 0-10 cm layer to 66.62% in the 60-80 cm layer. The second most important component is sodium sulfate (6.78-34.17%). It is significant that in the upper 0-40 cm layer there is sodium bicarbonate (18.78-25.48% of the total salts with an absolute content of 0.047-0.059%), which determines potential alkalinity and is the most toxic form for plants. Non-toxic salts (Ca $(HCO_3)_2$, $CaSO_4$) in the upper part of the profile are represented mainly by calcium bicarbonate (8.19-16.84%), and from a depth of 40 cm - by gypsum, the proportion of which reaches 18.70% in the 60-80 cm layer.

Table 2. Qualitative composition of soil salts in section P-1, % of the total salts.

Horizon, cm	Total salts, %	$Ca(HCO_3)_2$	$CaSO_4$	$NaHCO_3$	$MgSO_4$	Na_2SO_4	$MgCl_2$	NaCl	The amount of toxic salts
0-10	0,196	16,84	0,00	23,98	0,00	20,41	7,14	31,63	83,16
10-20	0,293	8,19	0,00	18,78	0,00	32,42	6,48	34,13	91,81
20-30	0,246	9,76	0,00	23,98	0,00	26,83	6,10	33,33	90,24
30-40	0,208	11,54	0,00	25,48	0,00	23,07	7,21	32,70	88,46
40-50	0,844	6,16	4,62	0,00	7,94	24,88	0,00	56,40	89,22
50-60	2,650	2,15	7,43	0,00	4,15	31,32	0,00	54,95	90,42
60-80	4,776	1,06	18,70	0,00	6,84	6,78	0,00	66,62	80,24
80-100	7,864	0,77	8,88	0,00	5,57	24,25	0,00	60,53	90,35
100-120	5,810	1,05	9,54	0,00	7,12	16,94	0,00	65,35	89,41
120-140	5,812	1,22	3,01	0,00	3,25	34,00	0,00	58,52	95,77
140-160	4,247	0,94	8,94	0,00	7,12	17,20	0,00	65,80	90,12
160-180	7,385	0,70	3,70	0,00	3,25	34,17	0,00	58,18	95,60
180-200	6,489	0,78	5,60	0,00	2,96	31,22	0,00	59,44	93,62

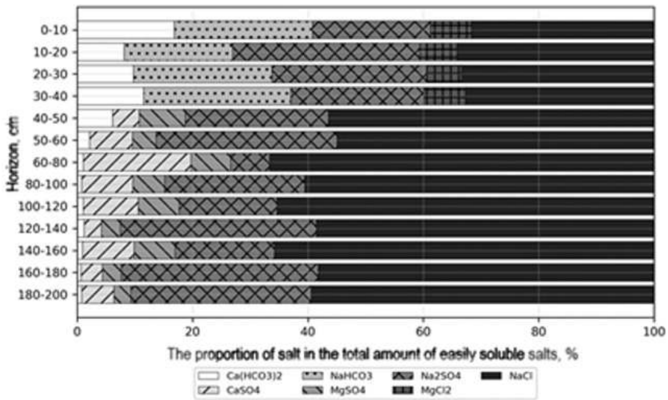

Figure 3. Qualitative composition of readily soluble salts by horizons of section P-1.

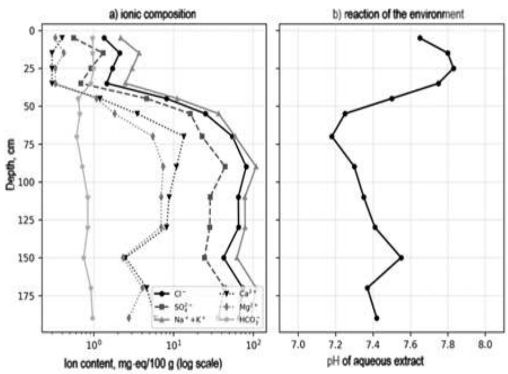

Figure 4. Ionic composition of the aqueous extract (a) and pH value (b) along the profile of section P-1.

Soil Absorption Complex Status. Exchangeable cation analysis (Table 3, Figure 5) revealed a high degree of sodium saturation in the root zone complex. Exchangeable sodium content increases from 9.0 mg-eq/100 g in the 0-10 cm layer to 20.75 mg-eq/100 g in the 50-60 cm layer, and its share of the total absorbed bases (TAB) is 26.5-40.1% with a solonetzic threshold of 15%. Thus, all studied horizons of the root zone are characterized as highly solonetzic. The calculated sodium adsorption index (SAR) increases consistently with depth from 3.6 (0-10 cm) to 22.5 (50-60 cm) and further to 52.0 (160-180 cm), confirming the increasing sodium impact. A high proportion of exchangeable sodium is an independent degradation factor: it causes peptization of colloids, structural destruction, reduced water permeability, and the formation of a surface crust, as confirmed by field observations of crust formation in northern desert soils (Mukhambetov et al., 2026). This circumstance explains the low field germination of seeds sown in winter with soil incorporation and serves as one of the arguments in favor of surface winter sowing on snow.

Table 3. Composition of absorbed bases, degree of solonetzization, and calculated SAR of soils in the pit P-1.

Horizon, cm	**Ca^{2+}, mg-eq/100 g**	**Mg^{2+}, mg-eq/100 g**	**Na^{+}, mg-eq/100 g**	**Summ, mg-eq/100 g**	**ESP (ESP), %**	**SAR, calcul.**	**Grade**
0-10	17,50	7,50	9,00	34,00	26,5	3,6	highly saline
10-20	17,00	7,00	14,20	38,20	37,2	6,2	highly saline
20-30	17,50	18,00	15,20	50,70	30,0	5,4	highly saline
30-40	17,00	8,50	14,40	39,90	36,1	4,4	highly saline
40-50	17,00	8,50	13,15	38,65	34,0	10,4	highly saline
50-60	23,50	7,50	20,75	51,75	40,1	22,5	highly saline

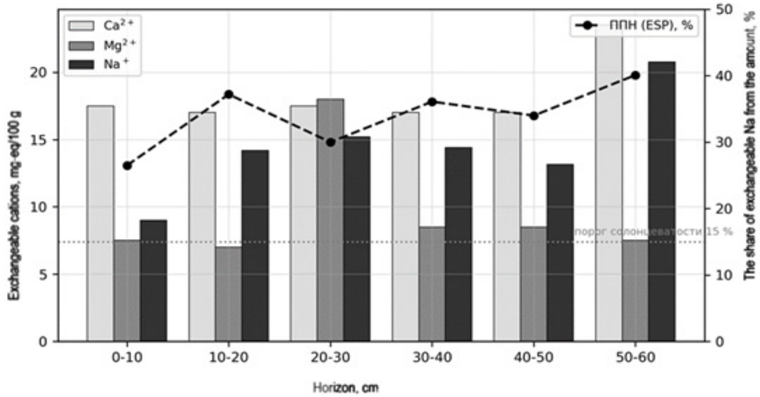

Figure 5. Composition of exchangeable cations and the proportion of exchangeable sodium (PES) in the 0-60 cm layer.

Humus status and nutrient status. The humus content of the studied soils is low and typical of brown desert soils: 1.14-1.45% in the 0-40 cm layer, dropping sharply to 0.70% in the 40-50 cm layer (Table 4, Figure 6). The maximum value is located in the 10-20 cm horizon (1.45%), indicating predominantly root-mediated organic matter input and weak humus accumulation on the surface under sparse vegetation cover.

The content of nitrate nitrogen (7.99-14.78 mg/100 g) and available phosphorus (7.88-12.04 mg/100 g) decreases with depth, synchronously with humus ($r = 0.91$ and 0.75, respectively), confirming the biogenic nature of their accumulation. A high exchangeable potassium content (26.23-58.23 mg/100 g) is a characteristic feature of soils formed on saline clay deposits. This nutrient balance (relative nitrogen and phosphorus deficiency with potassium excess) is typical of the region's arid soils and should be taken into account when developing phytomeliorant cultivation technologies.

Table 4. Content of humus and mobile forms of nutrients in the 0-50 cm layer.

Horizon, cm	Humus, %	$N\text{-}NO_3^-$, mg/100 g	P_2O_5, mg/100 g	K_2O, mg/100 g
0-10	1,14	13,99	12,04	58,23
10-20	1,45	14,78	11,64	59,19
20-30	1,25	12,03	10,10	46,68
30-40	1,24	12,55	9,58	35,61
40-50	0,70	7,99	7,88	26,23

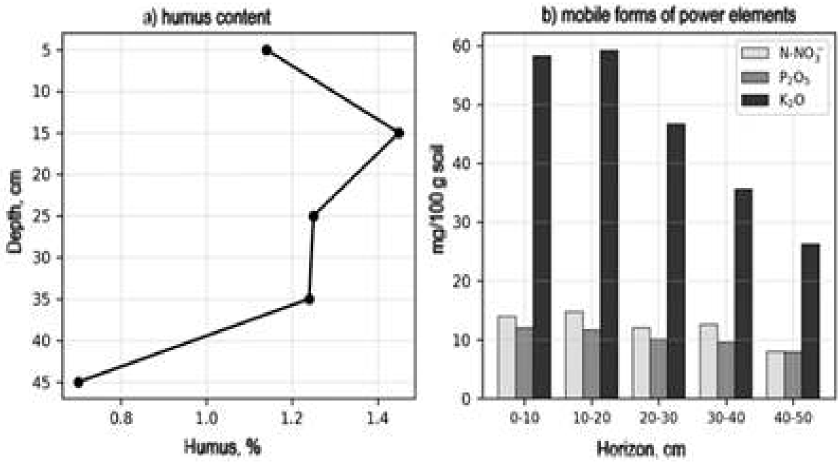

Figure 6. Humus content (a) and mobile forms of nutrients (b) in the 0-50 cm layer.

Particle size distribution. Based on physical clay content (particles <0.01 mm), the soils in the profile are classified as heavy loams and light clays: 46.66-63.34% in the 0-60 cm layer and up to 80.16% in the 80-100 cm layer (Table 5, Figure 7). The fine-grained fractions are dominated by particles 0.005-0.001 mm (32.4-38.0%) and 0.01-0.005 mm (12.4-50.8%), while the proportion of silt (<0.001 mm) does not exceed 1.86%.

The heavy particle size distribution has two fundamentally important consequences for phytomelioration. Firstly, the high sorption capacity and low water permeability of such soils prevent the natural leaching of salts by precipitation, which stabilizes the salt profile (a similar pattern has been observed for soils in the Zhetysu region - Madibekov et al., 2026). Secondly, the developed capillary system ensures intensive upward flow of solutions and secondary salt accumulation when the surface is exposed, making the creation of a closed vegetation cover a key antisalt protection technique. The increasing weight of the particle size distribution downwards (80.16% physical clay in the 80-100 cm layer) creates additional aquicludes, promoting the formation of perched water and the accumulation of salts precisely in the 60-100 cm interval, which is fully consistent with the location of the salt maximum (Figure 2, a).

Table 5. Granulometric composition of soils in section R-1.

Horizon, cm	1-0,25 mm	0,25-0,05 mm	0,05-0,01 mm	0,01-0,005 mm	0,005-0,001 mm	< 0,001 mm	Physical clay, %	Variety
0-10	0,26	29,60	6,80	24,80	37,60	0,94	63,34	light clay
10-20	0,34	34,40	4,40	23,20	36,80	0,86	60,86	light clay
20-30	0,16	35,20	5,60	21,20	37,60	0,24	55,50	heavy loam
30-40	0,20	25,60	16,40	19,20	38,00	0,60	57,80	heavy loam
40-50	0,14	43,60	9,60	12,40	32,40	1,86	46,66	heavy loam
50-60	0,10	36,80	4,00	23,20	35,20	0,70	59,10	heavy loam
60-80	3,18	20,40	16,00	50,80	8,80	0,82	60,42	light clay
80-100	0,64	10,80	8,40	42,00	38,00	0,16	80,16	medium clay

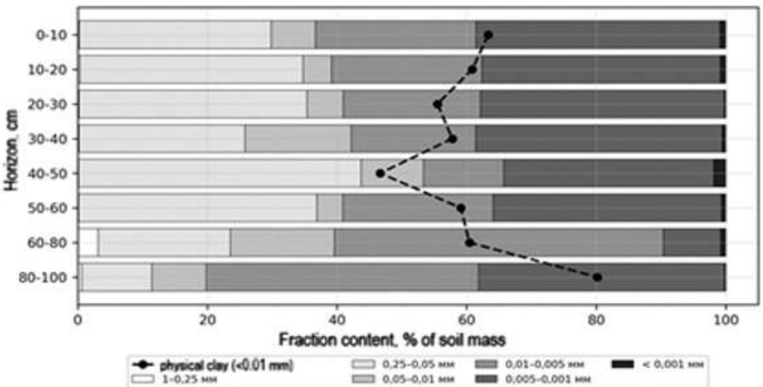

Figure 7. Granulometric composition of soils in section R-1 and physical clay content.

Scientific rationale for using Kochia prostrata for phytomelioration. Comparison of established soil geochemical parameters with experimentally determined salt tolerance thresholds of K. prostrata (Francois, 1976; Karimi et al., 2005; Sagers et al., 2017; Waldron et al., 2020) allows for a quantitative assessment of the suitability of the studied soils for phytomelioration (Figure 8, Table 6).

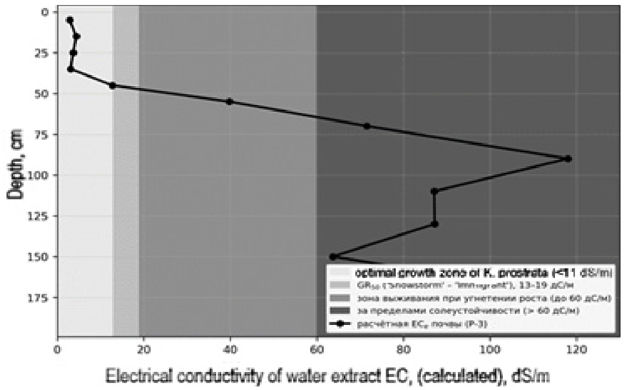

Figure 8. Comparison of the calculated electrical conductivity of the soil profile of section P-1 with the salt tolerance ranges of Kochia prostrata (according to Sagers et al., 2017; Waldron et al., 2020).

1. Correspondence of the rooting layer to the optimum zone. The calculated electrical conductivity of the 0-40 cm layer is 2.9-4.4 dS/m, which is significantly lower than the GR_{50} value for the least salt-tolerant variety 'Snowstorm' (130 mmol/L NaCl≈13 dS/m) and even less so for the variety 'Immigrant' (189 mmol/L≈19 dS/m). This layer is located in the zone where, according to Francois (1976), cypress produces a full-fledged crop. It is in this layer that the bulk of the plant's roots is concentrated in the first two years of life, and both tillering zones of the crop are located - the basal zone and the one located at a height of 10-20 cm (Mukhambetov et al., 2026). Consequently, the survival and initial development of cypress are limited not by the salinity factor, but by the water regime and the physical condition of the surface (crust formation).

2. The 40-60 cm salt barrier as a limiting factor. A sharp increase in salinity in the 40-60 cm layer (12.7-39.8 dS/m) means that already in the second year of life, when the cypress root system penetrates deeper than 40 cm, the plants enter the GR_{50} range and further into the zone of pronounced growth inhibition. This provides a geochemical explanation for the phenomenon of dwarfism of the cypress, previously described for the saline lands of the Northern Caspian region: plants retain viability (the mortality threshold, according to Sagers et al. (2017), corresponds to 600 mmol/L, i.e., ≈60 dS/m), but they reduce linear growth and accumulate excess ions in the aboveground mass. Horizons deeper than 60 cm (63.7-118.0 dS/m) extend beyond the salt tolerance of the species and should be considered as a salt screen impermeable to the roots.

3. Favorable salinity chemistry. The absence of carbonate ions and a neutral to slightly alkaline pH (pH 7.18-7.83) are crucial, as sodium salinity is toxic to halophytes at significantly lower concentrations than chloride-sulfate salinity. The predominance of NaCl and Na_2SO_4 corresponds to the salinity background against which the halophytic nature of K. prostrata was experimentally confirmed (Karimi

et al., 2005; Sagers et al., 2017). The presence of gypsum ($CaSO_4$) in amounts of 0.128-0.893% in the 40-200 cm layer is an additional favorable factor: the calcium in gypsum can displace exchangeable sodium from the soil-exchange complex when moisture arrives, enhancing the ameliorative effect of the plant cover. 4. Quantitative assessment of salt removal by biomass. With a salt content (NaCl + KCl) in the dry aboveground mass of 9-19% (Waldron et al., 2020) and a yield of 2.3-2.8 t/ha of dry matter, achieved in the northern desert of Western Kazakhstan (Mukhambetov et al., 2026), the annual removal of salts with mown biomass is 0.21-0.53 t/ha. The reserve of readily soluble salts in the 0-40 cm layer with an average concentration of 0.236% and a bulk density of 1.35 g/cm³ is estimated at 12.7 t/ha. Thus, 1.7-4.2% of the salt reserve of the root zone can be removed annually due to biomass alienation. This value shows that direct salt removal by the plant is not the main mechanism of desalination and that the phytomeliorative effect of K. prostrata is predominantly indirect.

5. Main mechanisms of the phytomeliorative effect. Based on the soil characteristics obtained, the leading mechanisms should be considered: (a) screening of the surface by a closed soil cover, which reduces physical evaporation and, accordingly, the ascending capillary current of salts from the 40-100 cm horizon, which is the determining factor with a heavy particle size distribution; (b) biological drainage and the creation of a system of root passages that increase the permeability of the solonetzic horizon; (c) accumulation of organic matter (with an initial humus content of 1.14-1.45%, even a small increase in it significantly improves the structural state and reduces crust formation); (d) displacement of exchangeable sodium by calcium mobilized from gypsum and $Ca(HCO_3)_2$ with increased biological activity of the rhizosphere. (d) protection of the surface from deflation, the probability of which in the region reaches 30-41% (Mukhambetov et al., 2026).

Conclusion. The saline soils of the northern desert subzone of the Atyrau Region exhibit a strongly differentiated vertical salinity profile. The surface 0-40 cm horizon is only slightly saline (0.196-0.293% readily soluble salts), whereas salt concentrations increase sharply to 0.844% at 40-50 cm, 2.650% at 50-60 cm, and reach a maximum of 7.864% in the 80-100 cm horizon. Soil salinity is characterized as sulphate-chloride sodium, with Cl^-/SO_4^{2-} ratios ranging from 1.54 to 2.41 and $Na^+/(Ca^{2+} + Mg^{2+})$ ratios of 3.0-12.9. Carbonate alkalinity was absent (CO_3^{2-} not detected), and soil pH remained within the neutral to slightly alkaline range (7.18-7.83).

Toxic salts constituted 80.2-95.8% of the total soluble salt content, with NaCl and Na_2SO_4 representing the dominant salt components. Although overall salinity in the surface horizon was relatively low, the presence of $NaHCO_3$ accounted for 18.8-25.5% of the soluble salts, indicating a potential risk for soil structural degradation and reduced seedling establishment.

The soil adsorption complex was characterized by pronounced sodicity, with exchangeable sodium comprising 26.5-40.1% of the cation exchange capacity and an estimated sodium adsorption ratio (SAR) of 3.6-22.5 within the upper 60 cm. Combined with the heavy loam to light clay texture, low humus content (0.70-1.45%), and limited nitrogen and phosphorus availability, these properties create unfavorable physical conditions, including poor infiltration, crust formation, and restricted root penetration.

Despite these limitations, the estimated salinity of the surface 0-40 cm horizon (ECe 2.9-4.4 dS m^{-1}) falls well within the optimal range reported for Kochia prostrata and remains substantially below the experimentally established GR_{50} threshold (approximately 13-19 dS m^{-1}). These findings demonstrate that surface soil salinity does not represent the principal constraint to plant establishment. Instead, the abrupt increase in salinity beginning at depths of 40-60 cm constitutes the major edaphic barrier limiting root development and long-term productivity.

Overall, this study provides the first integrated assessment linking the vertical geochemical characteristics of saline soils in the Atyrau Region with experimentally established salinity tolerance thresholds of *Kochia prostrata*. The results provide a scientific basis for selecting this species for phytomelioration of degraded saline rangelands and establish a reference dataset for long-term monitoring of soil reclamation processes and the development of region-specific strategies for sustainable pasture restoration in the Caspian Lowland.

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