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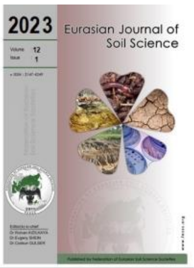

Effective strategies for reclaiming soda-saline soils: Field experimentation and practical applications in Southeast Kazakhstan

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Abstract

Soda-saline soils pose significant challenges to agricultural productivity, particularly in regions like the foothill plain of the Ili Alatau in southeast Kazakhstan. In this study, we examined the effectiveness of different ameliorants, including phosphogypsum, elemental sulfur, and sulfuric acid, in reclaiming soda-saline soils and enhancing crop yields. The study was conducted under real climatic and production conditions at the "Amiran" LLP farm. Using a randomized complete block design, we assessed the impact of these ameliorants on soil composition and alfalfa yield over two cutting cycles. The experiment involved the application of phosphogypsum, elemental sulfur, and sulfuric acid to designated plots within the farm, each covering an area of 15m2. Soil samples were collected before and after treatment to assess changes in soil composition and salinity. Alfalfa, a resilient perennial crop, was selected for cultivation due to its tolerance to adverse soil conditions. Our findings reveal that all tested ameliorants successfully neutralized the toxic environment of soda-saline soils, resulting in improved soil conditions and increased crop productivity. Phosphogypsum treatment led to a reduction in bicarbonate and carbonate ions, an increase in sulfate ion concentration, and improved soil structure. Elemental sulfur incubation decreased bicarbonate and carbonate ions, further reducing absorbed sodium levels and enhancing soil fertility. Sulfuric acid treatment provided rapid results in reducing alkalinity and increasing sulfate ion concentration, leading to significant improvements in soil quality and crop yield. However, the reclamation of soda-saline solonetzes presented challenges related to soil heterogeneity and poor water permeability. To address these challenges, we recommend the implementation of mechanical destruction of the solonetz soil horizon and deep soil loosening, accompanied by the addition of ameliorants. In conclusion, our study demonstrates the potential of phosphogypsum, elemental sulfur, and sulfuric acid as effective ameliorants for reclaiming soda-saline soils and improving agricultural productivity in challenging environments. By adopting recommended reclamation strategies, farmers can overcome soil limitations and achieve sustainable crop production in regions affected by soda-saline soil degradation

Keywords: Soil reclamation, soda-saline soils, elemental sülfür, phosphogypsum, sulfuric acid, agricultural productivity.

Introduction

Soil salinization and sodification remain significant challenges worldwide, particularly in arid and semi-arid regions. These phenomena not only hinder agricultural productivity but also jeopardize global food security (Negacz et al., 2022). The prevalence of saline and soda-affected soils continues to expand, driven by both natural processes and human activities such as unsustainable irrigation and drainage practices (FAO, 2015;

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Ivushkin et al., 2019). The consequences of soil salinization and sodification extend beyond diminished crop yields, disrupting vital soil processes and undermining soil biodiversity (Doula and Sarris, 2016).

Of particular concern are alkaline soda soils, which present formidable obstacles to reclamation due to their elevated levels of sodium, magnesium, and sodium carbonates and bicarbonates in the pore solution (FAO, 1984). In Kazakhstan, where fertile lands are interspersed with areas affected by soil salinity and sodicity, the need for effective reclamation strategies is paramount. In the foothill plains of southeast Kazakhstan, characterized by meadow, meadow-gray soil, and meadow-chestnut soils, substantial yield losses of 15% to 45% due to soda salinity have been observed (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).

Efforts to address soil salinity and sodicity in Kazakhstan have focused on the application of ameliorative techniques such as phosphogypsum, elemental sulfur, and sulfuric acid. Previous laboratory research has provided valuable insights into the physicochemical processes involved in soil reclamation, laying the groundwork for field experimentation (Hopmans et al., 2021). However, the translation of laboratory findings to real-world conditions is essential for developing effective soil reclamation strategies tailored to local environmental and climatic conditions (Shankar and Evelin, 2019).

This article presents the outcomes of a field experiment conducted in southeast Kazakhstan to evaluate the efficacy of various ameliorants in reclaiming soda-saline soils. Building upon the insights gained from laboratory studies, the field experiment aimed to elucidate the dynamics of ameliorant influence on soil salt regimes in actual environmental settings. By effectively managing the fertility of infertile soda-saline soils, the study contributes to the advancement of sustainable land management practices and agricultural productivity in saline-affected regions (Qadir and Schubert, 2002; Schirawski and Perlin, 2018). In summary, the field evaluation of ameliorants for reclaiming soda-saline soils represents a crucial step towards addressing the pressing challenge of soil salinity and sodicity in Kazakhstan. The findings offer practical insights into soil reclamation strategies tailored to the unique characteristics of saline-affected lands, paving the way for sustainable agricultural development and enhanced food security in the region.

Material and Methods

Site description

The field experimentation and soil sampling were conducted in the Talgar region of the Almaty province in Kazakhstan. The selection of the experimental site was based on comprehensive analyses of small, medium, and large-scale soil maps, emphasizing the distribution of alkaline soda-saline soils within the region. The specific coordinates of the site are N 43°39'7858, E 77°18'2917 (Figure 1). This area falls within the halogeochemical province characterized by the accumulation of sodic-sulfate salts from the Balkhash Lake basin. The climate in this region exhibits characteristics of continental and drought-prone conditions, with dry and hot summers. July typically sees average temperatures ranging from 22-25°C, while January averages range between 9-12°C. Annual precipitation averages around 250-300 mm, with an average annual air temperature of 9.8°C. The predominant soils in the study area are light meadow gray soils, with particular focus directed towards semi-hydromorphic heavy loamy solonetzes exhibiting sulfate-sodic, sodic-sulfate, and pure sodic chemistries. These soils cover approximately 10% of the total area under investigation.

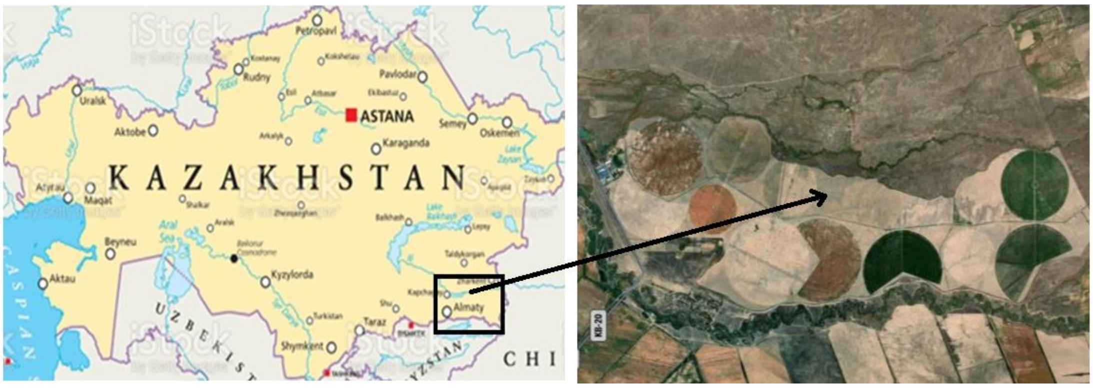

Figure 1. Location of the study area

Field Experiment and Soil Sampling

The field experiment was conducted at Amiran Farm in experimental field №8, dedicated to corn silage production within a crop rotation system. The area's soils exhibit diverse characteristics, ranging from meadow gray soils to light northern, weakly solonchakous-slightly solonchakous, and medium to strongly solonetzic types, with chloride-soda and soda-sulfate chemistry covering an expanse of 77 hectares. Notably, heavy loamy medium-salt semi-hydromorphic solonetzes, comprising approximately 10% (8 hectares) of the field, occur in the form of spots on microdepressions, displaying sulfate-soda, soda-sulfate, and pure soda chemistry. Solonetzes are marked by a dense clay horizon B, rich in adsorbed (exchangeable) Na^+ and occasionally Mg^{2+}. These soils also contain free soda (Na_2CO_3), contributing to a highly alkaline environment, which adversely affects corn growth, leading to sparse or complete absence in affected areas.

Figure 2. Condition of corn plants on the spotted soda-saline solonetz of the experimental plot

An experimental site was designated within one of these spots to evaluate the effectiveness of various ameliorants, including phosphogypsum, elemental powdered sulfur, and a 1% solution of sulfuric acid. The experiment was replicated four times to ensure robustness of results. Before initiating the field experiment, soil samples were collected from each plot and replicate at depths of 0-20 cm, 20-40 cm, and 40-60 cm to determine initial content of water-soluble salts, pH, and composition of absorbed bases (Ca, Mg, Na, K). Subsequent plowing and leveling prepared the experimental plot for further proceedings. Based on the experimental design, the plot was divided into randomly distributed plots, each covering an area of 5×3=15m^2. Following this, calculated doses of ameliorants were applied to the soil of the plots and thoroughly mixed. Periodic moistening was carried out to maintain optimal soil moisture levels.

Utilizing data on the initial physicochemical composition of semi-hydromorphic heavy loamy solonetzes, a comprehensive field experiment scheme was devised, incorporating phosphogypsum, powdered elemental sulfur, and a 1% solution of sulfuric acid. These were applied based on an equivalent dose of 1 ton of gypsum.

№	Variants	Doses of Ameliorating Substances
1	Control	-
2	Phosphogypsum	17.5 kg (per 15 m2) / 11.67 tons (per hectare)
3	Elemental Sulfur	6.66 kg (per 15 m2) / 2.22 tons (per hectare)
4	Sulfuric Acid, 1% Solution	9.97 kg (per 15 m2) / 6.652 tons (per hectare)

The fertility restoration of the 0-40 cm soil layer was determined using the formula:

$$G = 0.086 \times (Na^+ - 0.1xCEC) + [(CO_3^{2-} + HCO_3^-) - 1.0] \times H \times Bd;$$

here:

G	represents the amount of pure gypsum (100% $CaSO_4 \cdot 2H_2O$).
Na^+	is the amount of exchangeable sodium (me 100g^{-1}).
H	stands for the thickness of the reclamed layer (cm).
Bd	indicates the bulk density (g cm^3).
CEC	signifies the cation exchange capacity (me 100g^{-1}).
0.086	is the coefficient of conversion of calcium to gypsum.
1.0	represents the amount of (CO_3^{2-}+ HCO_3^-) in the water extract that is not harmful to plants (me 100g^{-1}).
0.1	is the coefficient allowing the preservation of 10% of exchangeable sodium in the soil absorbing complex of solonetzes.

The concentration of these ions (CO_3^{2-}+ HCO_3^-) in the water extract is measured in me 100g^{-1}. The presence of free soda in the soil necessitates an increase in ameliorating substances due to the presence of sodium carbonates and bicarbonates. Equivalent amounts of sulfur and sulfuric acid, in tons equivalent to 1 ton of pure gypsum, are 0.19 and 0.57, respectively. Calculations revealed that for medium and strong solonetz, the reclamation of a 0-40 cm layer requires 11.67 t/ha of gypsum or phosphogypsum, 2.22 t/ha of elemental sulfur, and 6.652 t/ha of sulfuric acid. The concentration of the latter was adjusted by diluting it with water to a 1% solution. In the variants utilizing phosphogypsum, sulfur, and sulfuric acid, the soil underwent plowing and washing with 1.5-2 volumes of water, equal to the total moisture capacity of the soil (5 m^3) with a volume of 4500 m^3/ha. Water supply was repeated three times every 5-6 days to ensure effective leaching after each release of the reclaimed soil layer from gravitational water (water of large and medium pores). The rinsing rate of water was determined using the formula of Volobuev (1975).

$$Q = Q1 + Q2 + Q3$$

where:

Q represents the leaching rate (m^3/ha).

Q1 denotes the amount of water in percentage that saturates the soil above natural moisture to the lowest moisture capacity (LMC), calculated as LMC-m.

mm signifies the reserve of natural humidity (in percentage).

Q2 indicates the amount of water (in percentage) saturating the soil above the LMC to the full moisture capacity (FMC), calculated as FMC-LMC.

Q3 represents the amount of water in m^3/ha filtered through the soil after it is completely saturated, expressed as a multiple of FMC or LMC by coefficient nn, depending on salinity, water-physical, and physicochemical properties of the soil, i.e. Q3=n x FMC x (LMC)

Before and after leaching, mixed soil samples from the experimental plots were collected and subjected to laboratory analysis, including the determination of the ionic composition (HCO3-, CO_3^{2-}, Cl^-, SO_4^{2-}, Ca^{2+}, Mg^{2+}, Na^+, K^+) of water extract from soils, salt content, pH levels, and the composition of absorbed cations (USDA, 2014; 2022). The toxicity threshold for individual ions in aqueous extracts from soil was used for classification according to Bazilevich and Pankov (1969). Statistical analysis was performed using one-way ANOVA and Tukey's multiple comparison tests to determine the significance of differences between the different ameliorants. The analysis was conducted in the R statistical software (v4.1.3).

Results and Discussion

Reclamation efficiency of phosphogypsum incubation, sulfur, and sulfuric acid application, and leaching on soda-saline soils

The geological dynamics within the middle segment of the Ili Depression have instigated a desalinization process within the upper layers of carbonate sulfate solonchaks. These solonchaks, primarily formed under effusive water regimes in preceding epochs, underwent transformation into solonchakous meadow gray soils due to prolonged and gradual infiltration of sodium sulfate-rich solutions through carbonate strata. This phenomenon eventually led to the development of soda semi-hydromorphic solonetzes (Sarybaeva and Naushabayev, 2021). The perpetual generation of soda compounds (Na_2CO_3, $NaHCO_3$) within the soil profile, facilitated by exchange reactions between sodium colloids and the soil solution, is intricately linked with groundwater dynamics. Consequently, any chemical reclamation endeavors targeting soda-saline soils within the saz zone of the foothill plain yield short-term efficacy.

Field experiments were conducted to investigate the initial ion composition in pore solutions and soil-absorbing complexes within a designated area. Ameliorants were applied to experimental variants characterized by mild to moderately saline conditions (Table 1). The soluble salt content in soil variants treated with phosphogypsum measured 0.578%, 0.492%, and 0.645% at three depths, while elemental sulfur-treated variants exhibited contents of 0.142%, 0.157%, and 0.304%, and sulfuric acid-treated variants had contents of 0.143%, 0.437%, and 0.487%. Notably, these alternatives displayed a salinity chemistry comprising sulfate-soda, soda-sulfate, and pure soda components. Moreover, the presence of ions (HCO_3^-, CO_3^{2-}) responsible for soil alkalinity ranged from 1.36 to 3.80 me $100g^{-1}$ and 0.16 to 0.88 me $100g^{-1}$soil within the 0-20 cm upper layer. The elevated levels of these ions, surpassing plant-toxic thresholds, contribute to a high alkalinity environment (pH~9.0). Additionally, the soil solution harbored sulfates exceeding toxicity thresholds (1.7 me $100g^{-1}$), while chlorine ions remained at insignificant levels below toxicity thresholds (<0.3 me $100g^{-1}$). Sodium ions predominated in the cationic composition, exceeding toxicity thresholds (>2.0 me $100g^{-1}$) by several folds (3.24–8.21 me $100g^{-1}$).

Analysis of absorbed exchangeable cations revealed that soils within experimental variants exhibited characteristics of sodium-magnesium solonetzes (Sn). These soils predominantly absorbed magnesium, followed by sodium, with their proportions ranging from 30.00 to 63.69% and from 10.78 to 19.00% of the cation exchange capacity (CEC) within the surface layer of experimental variants. The average absorption capacity varied from 10.83 to 17.95 me $100g^{-1}$ soil across experimental variants.

Table 1. Influence of incubation of ameliorants and leaching of soda-saline soils of semi-hydromorphic solonetzes of the experimental site on their salt regime

Ameliorants	Variants	Total salt, %	(me 100g^{-1})								pH	Salinity chemistary	Degree of salinity
			HCO_3^-	CO_3^{2-}	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	Na^+	K^+			
At the depth of 0-20 cm													
PG	C	0,578a	3,80a	0,88a	0,11ab	3,56b	0,24a	0,24bc	6,79a	0,20bc	9,15a	S/Sd	moderate
	BL	0,34bcd	0,82cde	0,10bcd	0,05b	3,94ab	1,71a	0,61abc	2,24bc	0,26ab	7,90cde	S	low
	AL	0,363bc	0,73cde	0,06cd	0,21a	4,15ab	1,00a	0,60abc	3,21bc	0,29ab	8,41bc	S	low
S/r	C	0,142d	1,48b	0,32b	0,11ab	0,16c	0,10a	0,19c	1,32c	0,15c	8,98ab	Sd	low
	BL	0,35bcd	0,69de	0,06cd	0,07ab	4,09ab	1,03a	0,52abc	3,04bc	0,27ab	7,70de	S	low
	AL	0,276cd	0,47e	0,02cd	0,12ab	3,39b	1,62a	1,00a	1,05c	0,33a	8,28cd	S	low
SA, 1%	C	0,143d	1,36bc	0,16bcd	0,11ab	0,35c	0,10a	0,38bc	1,21c	0,14c	9,22a	Sd	low
	BL	0,534ab	0,66de	0,10bcd	0,10ab	6,77a	1,67a	0,73ab	4,83ab	0,30a	7,40e	S	moderate
	AL	0,226cd	1,13bcd	0,22bc	0,07ab	1,81bc	0,22a	0,29bc	2,35bc	0,15c	8,47bc	Sd/S	low
At the depth of 20-40 cm													
PG	C	0,492ab	2,76a	1,04a	0,11a	3,56b	0,10b	0,10b	6,08ab	0,16bc	9,03bcd	Sd/S	moderate
	BL	0,432ab	1,89abc	0,40bc	0,03a	3,84b	0,12b	0,33ab	5,18ab	0,138bc	9,60ab	Sd/S	moderate
	AL	0,381b	0,82d	0,14c	0,09a	4,35ab	0,36ab	0,48ab	4,16b	0,26a	8,77cd	S	low
S/r	C	0,157c	1,36cd	0,32bc	0,11a	0,55c	0,10b	0,38ab	1,43c	0,11bc	8,90cd	Sd/S	low
	BL	0,427ab	1,72bc	0,28bc	0,05a	3,97b	0,14ab	0,35ab	5,08ab	0,17b	9,60ab	Sd/S	moderate
	AL	0,359b	1,01cd	0,10c	0,12a	3,80b	0,50a	0,48ab	3,71bc	0,24a	8,50de	Sd/S	low
SA, 1%	C	0,437ab	1,80bc	0,56b	0,07a	3,98b	0,10b	0,29ab	5,37ab	0,10c	9,24abc	Sd/S	moderate
	BL	0,595a	1,60bcd	0,58b	0,13a	6,45a	0,27ab	0,55a	7,2a	0,17b	9,85a	S	moderate
	AL	0,472ab	2,42ab	0,90a	0,07a	3,73b	0,10b	0,24ab	5,74ab	0,14bc	7,96e	Sd/S	moderate
At the depth of 40-60 cm													
PG	C	0,645a	2,48a	1,20a	0,15ab	6,03a	0,10bc	0,19b	8,21a	0,16ab	9,03d	Sd/S	strong
	BL	0,453bc	2,35ab	0,68bcd	0,04cd	3,60bc	0,12abc	0,38ab	5,36bc	0,14abc	10,1a	Sd/S	moderate
	AL	0,441bc	1,82abc	0,58cd	0,07bcd	4,01abc	0,12abc	0,22ab	5,38bc	0,17ab	9,69b	Sd/S	moderate
S/r	C	0,304c	1,72bc	0,56cd	0,11abc	2,20c	0,19a	0,48a	3,24c	0,13bc	8,92d	Sd/S	low
	BL	0,455bc	2,07abc	0,48d	0,02d	3,95abc	0,09c	0,26ab	5,54bc	0,15abc	10,0a	Sd/S	moderate
	AL	0,397bc	1,50c	0,32d	0,11abc	3,74bc	0,17ab	0,36ab	4,65bc	0,18a	9,12cd	Sd/S	low
SA, 1%	C	0,49abc	2,28ab	1,04ab	0,11abc	4,08abc	0,10bc	0,19b	6,08abc	0,10c	9,28c	Sd/S	moderate
	BL	0,565ab	1,78abc	0,64bcd	0,16a	5,74ab	0,10bc	0,39ab	7,03ab	0,17ab	10,0abc	Sd/S	moderate
	AL	0,47abc	2,16abc	0,94abc	0,07bcd	3,96abc	0,12abc	0,198b	5,74abc	0,14abc	11,46a	Sd/S	moderate
Toxicity threshold, me		0,1	0,8	0,03	0,3	1,7	-	-	2,0	-	-	-	-

PG – Phosphogypsum, S/r – sulfur, SA – sulfuric acid, C – control, BL – before leaching, AL – after leaching, S – sulfate, Sd – sodic

Table 2. Effect of incubation and leaching on the composition of absorbed cations of reclaimed soda-saline semi-hydromorphic solonetz of the experimental site

Ameliorants	Variants	me100g^{-1}					Solonetz degree
		Ca^{2+}	Mg^{2+}	Na^+	K^+	CEC	
At the depth of 0-20 cm							
Phosphogypsum	C	3,96b	10,40a	1,76abc	0,21a	16,33ab	SN
	BL	15,10a	4,83c	0,77bc	0,19a	20,89a	SRn1Msh
	AL	9,16ab	5,20c	0,51bc	0,18a	15,05ab	SRn1Msh
Sulfur	C	4,95b	6,93bc	1,83ab	0,21a	13,92b	SN
	BL	10,15ab	7,55abc	0,96abc	0,21a	18,87ab	SRn1Msh
	AL	9,90ab	7,06bc	0,31c	0,12a	17,39ab	SRn1Msh
Sulfuric acid 1%	C	6,44b	8,91ab	2,28a	0,32a	17,95ab	SN
	BL	9,16ab	7,79abc	1,11abc	0,26a	18,32ab	SRn1Msh
	AL	6,08b	5,44c	1,37abc	0,33a	13,22b	SRn1Msh
At the depth of 20-40 cm							
Phosphogypsum	C	3,47c	7,43a	4,24a	0,51a	15,65ab	SN
	BL	4,46bc	7,31a	2,29abc	0,27abc	14,33ab	SN
	AL	8,54a	7,06a	0,76c	0,19bc	16,55a	SRn1Msh
Sulfur	C	3,96bc	7,43a	2,00abc	0,00c	13,39ab	SN
	BL	5,32bc	7,18a	2,15abc	0,37ab	15,02ab	SN
	AL	6,81ab	7,06a	0,36c	0,22bc	14,45ab	SRn1Msh
Sulfuric acid 1%	C	3,96bc	7,92a	1,14bc	0,35ab	13,37ab	SN
	BL	4,70bc	6,06a	1,78bc	0,43ab	13,47ab	SN
	AL	3,09c	5,20a	3,28ab	0,39ab	11,96b	SN
At the depth of 40-60 cm							
Phosphogypsum	C	1,98c	8,42a	1,21a	0,47a	12,08a	SN
	BL	2,11c	7,31ab	1,88a	0,30abc	11,60a	SN
	AL	2,85bc	6,19ab	1,49a	0,31abc	10,84a	SN
Sulfur	C	4,46b	5,94b	1,87a	0,16c	12,43a	SN
	BL	3,10bc	6,44ab	2,21a	0,25bc	12,00a	SN
	AL	3,84bc	6,93ab	0,71a	0,29abc	11,77a	SN
Sulfuric acid 1%	C	6,93a	3,46c	1,62a	0,25bc	12,26a	SRn1Msh
	BL	3,59bc	6,43ab	1,51a	0,39ab	11,92a	SN
	AL	3,09bc	5,19bc	2,78a	0,40ab	11,46a	SN

Solonetz threshold - - - - - -

C – control, BL – before leaching, AL – after leaching, SN – solonetz, SRn$_1$Msh – meadowish sierozem northern

Overall, the soils at the experimental site were identified as heavy loamy sodium-magnesium solonetzes with mixed sulfate-soda, soda-sulfate, and pure soda chemistry, exhibiting weak to moderate salinity levels. Following the application of calculated equivalent doses of sulfur, phosphogypsum, and sulfuric acid to soda-saline solonetzes, their reclamation efficiency was assessed based on water extracts and absorbed base compositions before leaching (Table 1 and 2).

Investigation of the effects of incubation of phosphogypsum, sulfur, and sulfuric acid and leaching of reclaimed soils on alfalfa yield

The study aimed to assess the impact of incubation and leaching of reclaimed soils with phosphogypsum, elemental sulfur, and sulfuric acid on perennial grass yield (Figure 3). Alfalfa variety "Kokorai" was sowed in the spring at a seeding rate of 26 kg/ha. Variants treated with phosphogypsum and sulfur showed relatively good alfalfa green mass yield, crucial considering the challenge of obtaining a harvest on the soda-saline solonetzes of the experimental plot without ameliorants. The zero yield in the control variant underscored the necessity of ameliorants. The impediments to alfalfa seed germination included toxic soda and sulfates in the soil solution, adverse water-physical properties, and the formation of a dense crust.

Figure 3. Overview of the experimental plot and the alfalfa cultivated within

The control variant's soils, where alfalfa failed to grow, exhibited high levels of carbonate, bicarbonate ions, and sulfates. These ions' concentrations in the 0-40 cm soil layer averaged 0.59, 2.66, and 2.83 me $100g^{-1}$ soil, respectively, indicating a sulfate-soda and soda-sulfate salinity chemistry. Sodium dominated the cationic composition of the soil solution, averaging 5.00 me $100g^{-1}$ soil, indicating sodium-magnesium heavy solonetzes. The soil environment in the control plots was highly alkaline (pH 9.0). To facilitate alfalfa growth and development, the experimental variants received abundant irrigation.

Alfalfa seedlings sprouted across all replicates of variants with phosphogypsum, sulfur, and sulfuric acid, primarily in cracks after soil surface drying. Field germination averaged 80-85% per plot area unit ($15m^2$). The alfalfa leaves displayed varying shades of green. Within a year, a two-cutting yield of alfalfa green mass was achievable using the experimental variants.

Table 3 illustrates the effect of incubation of equivalent doses of phosphogypsum, sulfur, and sulfuric acid, and soil washing on alfalfa yield. The phosphogypsum-treated variant showed an average alfalfa fresh yield of 4.40 tons/ha for the first cutting cycle, with a corresponding dry matter yield of 2.948 tons/ha. Similarly, the sulfur-treated variant yielded 4.09 tons/ha of fresh alfalfa and 2.740 tons/ha of dry matter.

Table 3. Impact of incubation with phosphogypsum, sulfur, and sulfuric acid, and soil washing on alfalfa yield (2023)

№	Variants	Average alfalfa yield, ton/ha					
		Forage fresh yield		∑ for 1 year	Forage dry matter yield		∑ for 1 year
		Cutting cycle1	Cutting cycle2		Cutting cycle1	Cutting cycle2	
1	Control	0.00c	0.00b	0.00b	0.00a	0.000a	0.000a
2	Phosphogypsum	4.40ab	3.82a	8.22a	2.95b	2.559b	5.507b
3	Sulfur	4.09b	3.37ab	7.46a	2.74b	2.258b	4.998ab
4	Sulfuric acid 1%	6.54c	5.88c	12.42c	4.38c	3.940c	8.322c

The second cutting's alfalfa yield slightly decreased in the phosphogypsum and sulfur-treated variants, averaging 3.82 and 3.37 tons/ha, respectively. Notably, the sulfuric acid-treated variant demonstrated a higher yield of 6.54 tons/ha for the first cutting and 5.881 tons/ha for the second, with dry matter yields of 4.382 and 3.94 tons/ha, respectively. This resulted in an annual yield of 12.42 tons/ha of green mass and 8.322 tons/ha of dry hay, highlighting sulfuric acid's potential as a treatment option.

In summary, the experimental plot soils exhibited unfavorable compositions and properties, rendering vegetation growth nearly impossible without ameliorants. Reclamation efforts enabled satisfactory alfalfa harvest, with sulfuric acid proving the most effective among the tested ameliorants in terms of productivity.

Influence of ameliorant incubation and alfalfa cultivation on soil salt regime and absorbed cation composition

The efficacy of ameliorant incubation, including phosphogypsum, sulfur, and sulfuric acid, along with soil leaching and alfalfa cultivation during the summer-autumn growing season, was assessed to understand their impact on the ionic composition of soil water extracts at the experimental site. The results indicated a notable reduction in salinity towards weak levels. In contrast to post-leaching data, sulfate content decreased nearly twofold in the phosphogypsum variant, reaching 2.13 and 2.05 me 100g^{-1} soil in the upper layers (0–20 and 20–40 cm). Sulfur incubation similarly reduced sulfate content in the 20–40 cm layer to 2.66 me 100g^{-1} soil (from 3.80 me after leaching). Notably, sulfur treatment created more favorable conditions for alfalfa growth compared to phosphogypsum, despite retaining sulfate ions in the solution.

Incubation of sulfuric acid during alfalfa ontogenesis in the summer-autumn period led to an increase in hydrocarbonate and carbonate ions in weakly soda-saline and saline meadow gray soils, accompanied by a decrease in harmful sulfate and sodium ions below their toxicity thresholds compared to post-leaching data. However, there was a general trend of decreasing water-soluble salt content in the soil solution, counteracted by increased ion concentration due to environmental factors such as elevated air and soil temperatures and intensified plant evaporation. The impact of ameliorant incubation, leaching, and alfalfa cultivation on soil salt regime was further evaluated through Table 4, showing variations in salt content across different treatments and depths. Phosphogypsum and sulfur incubation, along with alfalfa cultivation, contributed to sodium neutralization in the soils, approaching non-solonetz levels. However, the proportion of absorbed magnesium increased, indicating changes in soil-absorbing complex composition. Similar trends were observed with elemental sulfur, albeit with a higher proportion of magnesium.

Table 4. Effect of incubation of ameliorants, leaching and cultivation of alfalfa on the salt regime of soils in the experimental plot, me, August 2023

Ameliorants	Variants	Total salt, %	me 100g^{-1} soil								pH	Salinity chemistry	Degree of salinity
			HCO_3^-	CO_3^{2-}	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	Na^+	K^+			
PG	C	0,210a	0,73cd	0,10de	0,07a	2,13ab	1,12ab	0,62ab	1,01bc	0,19ab	8,6d	Sd/S	Low
	BL	0,276a	1,6abcd	0,50abcd	0,07a	2,05ab	0,12b	0,88a	2,58abc	0,15b	9,7ab	Sd/S	Low
	AL	0,260a	1,89ab	0,60abc	0,08a	1,39ab	0,10b	0,34ab	2,80a	0,14b	9,9ab	S/Sd	Low
S/r	C	0,288a	0,54d	0,00e	0,06a	3,54a	2,09a	0,96a	0,86c	0,24a	8,7cd	S	Low
	BL	0,273a	1,04bcd	0,24cde	0,06a	2,66ab	0,58ab	0,72ab	2,28abc	0,19ab	9,3bc	Sd/S	Low
	AL	0,260a	1,77abc	0,62abc	0,09a	1,52ab	0,10b	0,39ab	2,77a	0,13b	10,1a	S/Sd	Low
SA, 1%	C	0,162a	1,37abcd	0,28dcde	0,06a	0,69b	0,18b	0,69ab	1,13abc	0,13b	8,6d	S/Sd	Low
	BL	0,220a	2,10ab	0,66ab	0,06a	0,61b	0,15b	0,43ab	2,08abc	0,13b	10,0ab	Sd	Low
	AL	0,247a	2,26a	0,84a	0,05a	0,78b	0,10b	0,22b	2,66ab	0,12b	10,3a	Sd	Low
Toxicity threshold, me		0,1	0,8	0,03	0,3	1,7	-	-	2,0	-	-	-	-

PG – Phosphogypsum, S/r – sulfur, SA – sulfuric acid, C – control, BL – before leaching, AL – after leaching, S – sulfate, Sd – sodic

Table 5 illustrates the effect of ameliorant incubation and phytomelioration on absorbed bases of mixed soda-saline meadow gray soils. Notably, long-term sulfuric acid addition significantly decreased absorbed sodium while increasing absorbed magnesium in the upper soil layers, emphasizing its potential in altering soil cation composition.

Table 5. Effect of incubation of equivalent doses of ameliorants and phytomelioration on the absorbed bases of mixed soda-saline meadow gray soils, August 2023

Ameliorants	Variants	Absorbed cations, me 100g^{-1}				CEC, me 100g^{-1}	Solonetz degree	
		Ca^{2+}	Mg^{2+}	Na^+	K^+		Mg^{2+}	Na^+
Phosphogypsum	C	9,04a	7,06a	0,16ab	0,23bc	16,49a	SN	SRn1Msh
	BL	6,19abc	7,18a	0,65b	0,24bc	14,26a	SN	SRn1Msh
	AL	5,94abc	6,56a	1,01b	0,22bc	13,73a	SN	SRn1Msh^{SN1}
Sulfur	C	10,03a	8,42a	0,20b	0,21c	18,86a	SN	SRn1Msh
	BL	7,31ab	8,17a	1,17b	0,24bc	16,89a	SN	SRn1Msh$^{SN'}$
	AL	2,60cd	9,16a	1,41ab	0,28abc	13,45a	SN	SRn1Msh$^{SN''}$
Sulfuric acid 1%	C	6,31abc	7,31a	0,79b	0,27abc	14,68a	SN	SRn1Msh$^{SN'}$
	BL	4,21bcd	7,31a	1,67b	0,31a	13,50a	SN	SRn1Msh$^{SN''}$
	AL	1,74d	9,28a	3,00a	0,29ab	14,31a	SN	SN
Solonetz threshold		-	-	-	-	-	-	-

C – control, BL – before leaching, AL – after leaching, SN – solonetz, SRn_1Msh – meadowish sierozem nothern

Overall, these findings underscore the efficacy of ameliorant incubation and alfalfa cultivation in mitigating soil salinity and altering absorbed cation composition, highlighting their potential for soil reclamation and sustainable agriculture practices.

The study aimed to evaluate the comparative effectiveness of phosphogypsum, elemental sulfur, and sulfuric acid in reclaiming soda-saline solonetzes, focusing on their impact on soil salt regimes during incubation, leaching, and alfalfa cultivation. Overall, the results indicate that all tested ameliorants effectively altered the ion composition of the soil solution compared to the control group, suggesting their potential for soil reclamation.

Phosphogypsum, sulfur, and sulfuric acid treatments led to a notable reduction in bicarbonate and carbonate ions, thus mitigating soil alkalinity. However, distinct differences were observed in sulfate ion concentrations among the treatments. Particularly, sulfuric acid treatment significantly increased sulfate ion levels in the soil solution by displacing absorbed sodium with calcium ions, transforming the soil chemistry to a pure sulfate composition. This highlights sulfuric acid's effectiveness in reducing soil salinity.

Among the ameliorants, sulfuric acid demonstrated exceptional efficacy in shifting the soil's salinity chemistry towards a pure sulfate composition. This was attributed to the displacement of absorbed sodium by calcium ions from the soil-absorbing complex (SAC), resulting in an increased sulfate ion concentration in the solution. Additionally, sulfuric acid facilitated the leaching of reaction products, leading to a notable decrease in sulfate ion content in the soil solution. In contrast, sulfur treatment showed significant potential in reducing bicarbonate and normal carbonate ion levels in the soil solution, particularly in the upper layer. Despite retaining sulfate ions, sulfur-treated soils exhibited favorable conditions for alfalfa growth, indicating its effectiveness in ameliorating soil alkalinity. Phosphogypsum also showed promising outcomes, albeit with slight variations in ion composition compared to sulfur and sulfuric acid treatments. While phosphogypsum led to a higher sulfate ion content, it demonstrated properties conducive to improving soil structure, as observed during field observations. The reduction in absorbed sodium proportion relative to other cations in treated soils indicated the creation of more favorable conditions for crop growth and development. Alfalfa cultivation, particularly in phosphogypsum and sulfur-treated soils, not only enhanced soil structure but also improved soil nutritional regimes. However, the increased proportion of absorbed magnesium in almost all experimental variants warrants further investigation into its implications for soil fertility and crop productivity. Among the ameliorants, sulfuric acid emerged as the most efficient option in terms of incubation time and alfalfa yield, suggesting its potential for soil reclamation in sodic soils.

Given the unique characteristics of solonetzic soils, mechanical interventions such as deep soil destruction and loosening using specialized equipment are essential for effective ameliorant incorporation. This approach facilitates the penetration of ameliorants, such as phosphogypsum and sulfur, into deeper soil horizons, thereby enhancing their efficacy in soil reclamation.

Conclusion

The study addressed the pressing challenge of soil salinity and sodicity, particularly in arid and semi-arid regions, by evaluating the effectiveness of various ameliorants in reclaiming soda-saline solonetzes in southeast Kazakhstan. Against the backdrop of expanding saline and soda-affected soils globally, including in Kazakhstan, where these soils threaten agricultural productivity and food security, our research aimed to contribute to the development of effective soil reclamation strategies. Through a comprehensive field experiment, incorporating phosphogypsum, elemental sulfur, and sulfuric acid, we observed promising outcomes in altering the ion composition of the soil solution and mitigating soil alkalinity. All tested ameliorants effectively reduced bicarbonate and carbonate ions, thus alleviating soil alkalinity, which is detrimental to crop growth.

Sulfuric acid emerged as a particularly efficient option, demonstrating exceptional efficacy in transforming the soil's salinity chemistry into a pure sulfate composition. By displacing absorbed sodium with calcium ions and facilitating leaching, sulfuric acid not only reduced soil salinity but also improved soil structure, as evidenced by field observations. Sulfur and phosphogypsum treatments also showed promising results, albeit with slight variations in ion composition compared to sulfuric acid. While sulfur effectively reduced bicarbonate and carbonate ion levels, phosphogypsum contributed to improving soil structure, enhancing soil nutritional regimes, and reducing absorbed sodium proportion. The successful cultivation of alfalfa in treated soils further underscored the effectiveness of the reclamation strategies, with sulfuric acid exhibiting the most significant impact on alfalfa yield. However, the increased proportion of absorbed magnesium in treated soils warrants further investigation into its implications for soil fertility and crop productivity. Mechanical interventions such as deep soil destruction and loosening are essential for effective ameliorant incorporation, particularly in solonetzic soils. These interventions facilitate the penetration of ameliorants into deeper soil horizons, enhancing their efficacy in soil reclamation and paving the way for sustainable agricultural development in saline-affected regions.

In conclusion, our study offers practical insights into soil reclamation strategies tailored to the unique characteristics of saline-affected lands, contributing to the advancement of sustainable land management practices and agricultural productivity in Kazakhstan and similar regions worldwide.

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References

Bazilevich, N.I., Pankova, E.I., 1969. Classification of soils according to their chemistry and degree of salinization. *Agrokémia és talajtan* 18 (sup). pp. 219-226. [in Russian].

Doula, M.K., Sarris, A., 2016. Soil environment. In: Environment and Development : Basic Principles, Human Activities, and Environmental Implications. Poulopoulos, S.G., Inglezakis, V.J. (Eds.). Elsevier, pp. 213-286.

FAO, 1984. Prognosis of salinity and alkalinity. FAO Soils Bulletins No. 31. Food and Agriculture Organization of the United Nations. Rome, Italy, 260p. Available at [Access date: 07.12.2023]: https://www.fao.org/4/ar112e/ar112e.pdf

FAO, 2015. Status of the World's Soil Resources: Main Report. Food and Agriculture Organization of the United Nations and Intergovernmental Technical Panel on Soils (ITPS), Rome, Italy, 650p. Available at [Access date: 07.12.2023]: https://openknowledge.fao.org/server/api/core/bitstreams/6ec24d75-19bd-4f1f-b1c5-5becf50d0871/content

Funakawa, S., Suzuki, R., Karbozova, E., Kosaki, T., Ishida, N., 2000. Salt-affected soils under rice-based irrigation agriculture in Southern Kazakhstan. *Geoderma* 97(1-2): 61–85.

Hopmans, J. W., Qureshi, A. S., Kisekka, I., Munns, R., Grattan, S. R., Rengasamy, P., Ben-Gal, A., Assouline, S., Javaux, M., Minhas, P.S., Raats, P.A.C., Skaggs, T.H., Wang, G., De Jong van Lier, Q., Jiao, H., Lavado, R.S., Lazarovitch, N., Li, B., Taleisnik, E., 2021. Critical knowledge gaps and research priorities in global soil salinity. *Advances in Agronomy* 169: 1-191.

Ivushkin, K., Bartholomeus, H., Bregt, A. K., Pulatov, A., Kempen, B., de Sousa, L., 2019. Global mapping of soil salinity change. *Remote Sensing of Environment* 231: 111260.

Kussainova, M., Spaeth, K., Zhaparkulova, E., 2020. Efficiency of using the rangeland hydrology and erosion model for assessing the degradation of pastures and forage lands in Aydarly, Kazakhstan. *Eurasian Journal of Soil Science* 9(2): 186 - 193.

Laiskhanov, S.U., Otarov, A., Savin, I.Y., Tanirbergenov, S.I., Mamutov, Z.U., Duisekov, S.N., Zhogolev, A., 2016. Dynamics of soil salinity in irrigation areas in South Kazakhstan. *Polish Journal of Environmental Studies* 25(6): 2469–2476.

Liu, W., Ma, L., Smanov, Z., Samarkhanov, K., Abuduwaili, J., 2022. Clarifying soil texture and salinity using local spatial statistics (Getis-Ord Gi* and Moran's I) in Kazakh–Uzbekistan Border Area, Central Asia. *Agronomy* 12: 332.

Ma, L., Abuduwaili, J., Smanov, Z., Ge, Y., Samarkhanov, K., Saparov, G., Issanova, G., 2019 Spatial and vertical variations and heavy metal enrichments in irrigated soils of the Syr Darya River watershed, Aral Sea Basin, Kazakhstan. *International Journal of Environmental Research and Public Health* 16(22):4398.

Negacz, K., Malek, Ž., de Vos, A., Vellinga, P., 2022. Saline soils worldwide: Identifying the most promising areas for saline agriculture. *Journal of Arid Environments* 203: 104775.

Otarov, A., 2014. Concentration of heavy metals in irrigated soils in Southern Kazakhstan. In: Novel measurement and assessment tools for monitoring and management of land and water resources in agricultural landscapes of Central Asia. Mueller, L., Saparov, A., Lischeid, G. (Eds.). Environmental Science and Engineering. Springer, Cham. pp 641–652.

Pachikin, K., Erokhina, O., Funakawa, S., 2014. Soils of Kazakhstan, their distribution and mapping. In: Novel measurement and assessment tools for monitoring and management of land and water resources in agricultural landscapes of Central Asia. Mueller, L., Saparov, A., Lischeid, G. (Eds.). Environmental Science and Engineering. Springer, Cham. pp 519–533.

Qadir, M., Schubert, S., 2002. Degradation processes and nutrient constraints in sodic soils. *Land Degradation & Development 13*(4): 275-294.

Saparov, A., 2014. Soil resources of the Republic of Kazakhstan: Current status, problems and solutions. In: Novel measurement and assessment tools for monitoring and management of land and water resources in agricultural landscapes of Central Asia. Mueller, L., Saparov, A., Lischeid, G. (Eds.). Environmental Science and Engineering. Springer, Cham. pp 61–73.

Sarybaeva, G.M., Naushabayev, A.K., 2021. Formation of Soda-Saline Semi-Hydromorphic Solonetz of The Ili Depression. *Izdenister Natigeler* 2(90): 192–204. [in Russian].

Schirawski, J., Perlin, M.H., 2018. Plant–microbe interaction 2017—the good, the bad and the diverse. *International Journal of Molecular Sciences 19*(5): 1374.

Shankar, V., Evelin, H., 2019. Strategies for reclamation of saline soils. In: Microorganisms in Saline Environments: Strategies and Functions. Giri, B., Varma, A. (Eds.). Soil Biology, vol 56. Springer, Cham. pp. 439-449.

Suska-Malawska, M., Sulwiński, M., Wilk, M., Otarov, A., Metrak, M., 2019. Potential eolian dust contribution to accumulation of selected heavy metals and rare earth elements in the aboveground biomass of Tamarix spp. from saline soils in Kazakhstan. *Environmental Monitoring and Assessment* 191: 57.

Suska-Malawska, M., Vyrakhamanova, A., Ibraeva, M., Poshanov, M., Sulwiński, M., Toderich, K., Metrak, M., 2022. Spatial and in-depth distribution of soil salinity and heavy metals (Pb, Zn, Cd, Ni, Cu) in arable irrigated soils in Southern Kazakhstan. *Agronomy* 12: 1207.

USDA, 2014. Soil Survey Field and Laboratory Methods Manual. Soil Survey Investigations Report No. 51, Version 2. United States Department of Agriculture (USDA), Natural Resources Conservation Service, Kellogg Soil Survey Laboratory. 457p. Available at [Access date: 07.12.2023]: https://www.nrcs.usda.gov/sites/default/files/2023-01/SSIR51.pdf

USDA, 2022. Kellogg Soil Survey Laboratory Methods Manual. Soil Survey Investigations Report No. 42, Version 6.0. Part 1: Current Methods. Kellogg Soil Survey Laboratory, National Soil Survey Center, Natural Resources Conservation Service, United States Department of Agriculture (USDA). 796p. Available at [Access date: 07.12.2023]: https://www.nrcs.usda.gov/sites/default/files/2022-10/SSIR42-v6-pt1.pdf

Volobuev, V.R., 1975. Calculation of washing saline soils. Kolos, Moscow.

Yertayeva, Z. , Kızılkaya, R., Kaldybayev, S., Seitkali, N., Abdraimova, N., Zhamangarayeva, A., 2019. Changes in biological soil quality indicators under saline soil condition after amelioration with alfalfa (Medicago sativa L.) cultivation in meadow Solonchak. *Eurasian Journal of Soil Science* 8 (3): 189-195.

Zhang, W., Ma, L., Abuduwaili, J., Ge, Y., Issanova, G., Saparov, G., 2019. Hydrochemical characteristics and irrigation suitability of surface water in the Syr Darya River, Kazakhstan. *Environmental Monitoring and Assessment* 191: 572.