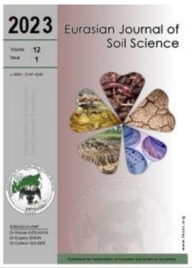
Eurasian Journal of Soil Science 2023, 12(4), 328 - 334

Eurasian Journal of Soil Science

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



Assessing the efficacy of ameliorants on saline-sodic soils: Laboratory insights for reclamation strategies

Nurzikhan Seitkali [a,*], Askhat Naushabayev [a], Shynar Mazkirat [b], Tursunay Vassilina [a]

[a] Kazakh National Agrarian Research University, Almaty, Kazakhstan
[b] Kazakh Research Institute of Agriculture and Crop Production, Almaty, Kazakhstan

Article Info
Received : 04.11.2022
Accepted : 17.07.2023
Available online : 24.07.2023

Author(s)
N.Seitkali *
A.Naushabayev
S.Mazkirat
T.Vassilina

* Corresponding author

Abstract

This study presents the combined findings of laboratory experiments conducted to assess the efficacy of various ameliorants on saline-sodic soils in the foothill plain of Ile Alatau in the Northern Tianshan region. The investigation focused on the influence of phosphogypsum, elemental sulfur, nano sulfur, and sulfuric acid on the ionic composition of the soil solution and their impact on the soil-absorbing complex. Different doses of these ameliorants were applied to saline-sodic soil samples, and their incubation period was observed. The analysis of the aqueous extract of the soil emphasized the presence of bicarbonate, carbonate, sulfate, calcium, and sodium ions. The results revealed that sulfuric acid was the most effective ameliorant, rapidly neutralizing extreme alkalinity, reducing bicarbonate and carbonate ion content, and increasing sulfate and sodium ion concentrations. Elemental sulfur ranked second in effectiveness, significantly decreasing bicarbonate and carbonate ions and increasing sulfate and sodium ions. Phosphogypsum exhibited the lowest effectiveness, causing reductions in bicarbonate and carbonate ions and modest increases in sulfate and calcium ions. The study demonstrated that the introduction of phosphogypsum led to an increase in calcium and sulfate ions in the soil solution, while elemental sulfur and sulfuric acid significantly increased the sulfate ion content. Sulfuric acid exhibited the highest efficacy among the ameliorants, completely neutralizing normal carbonates and reducing alkalinity in the soil solution. The formation of subsoil gypsum through the interaction of sulfuric acid with calcium carbonates facilitated the displacement of sodium from the soil-absorbing complex. These findings contribute to our understanding of the processes involved in the amelioration of saline-sodic soils and provide insights into effective soil management practices. They serve as a theoretical basis for developing strategies for the reclamation of such soils worldwide. The research highlights sulfuric acid as the most effective ameliorant for saline-sodic soils, resulting in a significant rearrangement of the soil's ionic composition. Further research and field studies are necessary to validate and refine these laboratory findings for practical applications in soil improvement methods.

Keywords: Saline-sodic soils, ameliorants, soil reclamation, Soil management.

Introduction

Soil salinization is a widespread issue, particularly in arid and semi-arid regions, and it poses a significant challenge to global agricultural production (El hasini et al., 2019). Saline soils are prevalent in arid areas due to limited rainfall, which hinders the leaching and transport of salts, and the high evaporation rates that lead to salt concentration in soils and surface waters. The expansion of salinity-affected land is estimated to increase at a rate of approximately 1-2% annually, attributed to factors such as global climate change and improper irrigation and tillage practices. These saline soils contain high concentrations (> 0.25%) of soluble salts in all soil layers, which are toxic to plants and hinder their growth (Shaygan and Baumgartl, 2022).

: https://doi.org/10.18393/ejss.1331960
: http://ejss.fesss.org/10.18393/ejss.1331960
Publisher : Federation of Eurasian Soil Science Societies
e-ISSN : 2147-4249

Sodic and saline-sodic soils exhibit poor physical properties and fertility issues that negatively impact the growth and yield of most crops (Rengasamy, 2002; 2006). Saline-sodic soils are found across various continents, ranging from tropical to polar zones, but they are most common in the Northern Hemisphere. In the Commonwealth of Independent States (CIS), the area covered by saline-sodic soils amounts to 120 million hectares, and the escalating expansion of these soils has made their reclamation a prominent concern in modern soil science (Yertayeva et al., 2019).

Kazakhstan, a country located mostly within the largest drainless part of the plain, faces an uneven distribution of saline soils. Approximately 70% of the saline soils in the Commonwealth of Independent States are located in Kazakhstan, covering an area of 111.55 million hectares, which accounts for 41% of the national territory. Central Asia, including Kazakhstan, is situated in the most saline part of the planet's land, with 191 million hectares of saline soils, equivalent to the combined area of soils in Africa and America. Salty soils in Kazakhstan are widespread, with solonetzes and solonetsous soils predominant in the northern and central parts, and solonchaks and solonchak soils dominating the southern, southwestern, and southeastern regions. Based on salt accumulation, four halogeochemical regions have been identified, namely the Caspian Sea basin (accumulation of sulfate-chloride and chloride salts), the Aral Sea basin (accumulation of chloride-sulfate salts), the Karsk Sea basin (accumulation of chloride-sulfate salts), and the Balkash Lake basin (accumulation of sodic-sulfate salts). In the southern, southwestern, and southeastern regions of Kazakhstan, the area covered by saline-sodic soils is approximately 7.095 million hectares, with distribution percentages of 18.6% in Almaty, 47.7% in Dzhambul, 27.3% in South Kazakhstan, and 21.7% in Kyzylorda. The presence of sodic-salinity among the highly fertile soils of the foothill color of the Northern Tien Shan, including meadow, meadow-serozem, and meadow-chestnut soils, accentuates the significance of addressing soil fertility issues. Crop losses due to sodic salinity in these areas range from 15% to 45% (Funakawa et al., 2000; Saparov, 2014; Pachikin et al., 2014; Otarov, 2014; Laiskhanov et al., 2016; Suska-Malawska et al., 2019; Zhang et al., 2019; Ma et al., 2019; Yertayeva et al., 2019; Kussainova et al., 2020; Liu et al., 2022; Suska-Malawska et al., 2022). Peasant farms annually apply various agricultural practices, from plowing to harvesting, to address saline-sodic soil patches. However, the low yields from these patches result in significant depreciation of material, monetary, and labor resources. Hence, the urgent need for saline-sodic soil reclamation in irrigated agricultural zones is evident.

The reclamation of saline or saline-sodic soils is a crucial global objective. Successful reclamation for agricultural purposes depends on understanding sodium dynamics and the chemical interactions that govern nutrient availability. Various methods are employed for the reclamation of saline soils, including physical techniques such as deep plowing, subsoiling, sanding, and profile inversion; chemical approaches involving amendments with substances like gypsum, calcium chloride, limestone, sulfuric acid, sulfur, and iron sulfate; and electro-reclamation techniques that utilize electric current treatment. The most effective methods involve the removal and exchange of soluble sodium, as well as modifying the ionic composition of soils through the addition of chemicals while simultaneously leaching sodium salts from the soil profile (Shaygan and Baumgartl, 2022).

To gain better control over soil fertility, it is crucial to understand the mechanisms underlying physicochemical and biological processes during the reclamation of saline-sodic soils under strictly controlled conditions. Laboratory research aimed at assessing the comparative effectiveness of different ameliorative techniques employing various rates of phosphogypsum, elemental sulfur, and sulfuric acid on saline-sodic soils can contribute to the development of effective soil amelioration technologies for saline-sodic soils.

Material and Methods

Site description

The soil sampling and laboratory experiment were conducted in the Talgar area of the Almaty region in Kazakhstan. The field plot was selected based on small, medium, and large-scale soil maps and soil reports, focusing on the distribution of alkaline soda-saline soils in the region. The specific coordinates of the site are N 43°39'7858, E 77°18'2917 (Figure 1). The selected region belongs to the halogeochemical province of accumulation of sodic-sulfate salts of the Balkhash Lake basin. The climate in the area is characterized by continentality and drought, with dry and hot summers. The average temperature in July ranges from 22-25°C, while in January, it is 9-12°C. The annual precipitation is 250-300 mm, and the average annual air temperature is 9.8˚C. The main background soils in the field plot are light meadow gray soils, but the focus of the study was on the small and medium semi-hydromorphic heavy loamy solonetzes with sulfate-sodic, sodic-sulfate, and pure sodic chemism. These soils occupy approximately 10% of the field.

Figure 1. Partial Snapshot of the Experimental Site Showing Soil Sample Locations

Soil sampling and lab experiment

Soil samples were taken from the upper layers (0-40 cm) of the identified spots of semi-hydromorphic heavy loamy solonetzes. The laboratory experiment involved the following ameliorative techniques: phosphogypsum, elemental sulfur (powdered and nano), and sulfuric acid (1%, 3%, and 5%). These ameliorants were thoroughly mixed with the soil and placed in plastic cups with a volume of 175 cm^2. The samples were kept at room temperature (23°C), and the soil moisture was maintained at 21%, corresponding to 70% of the field's water-holding capacity.

The calculations for the application of ameliorants were based on the initial physicochemical composition of the soil, and the doses were determined according to the formulas and coefficients specific to each ameliorant. The equivalent doses of ameliorants applied to the saline-sodic soils are presented in Table 1.

Table 1. The equivalent doses of ameliorants applied to soda-saline soils

Variants		Doses of introduced ameliorants	
		g 100g $^{-1}$	ton/ha
Control		-	-
Phosphogypsum	$PG_{1.0}$	0.218 (estimated)	11.67
	$PG_{1.5}$	0.327	17.50
	$PG_{2.0}$	0.436	23.34
Elemental sulfur	$S_{1.0}$	0.041 (estimated)	2.217
	$S_{1.5}$	0.062	3.325
	$S_{2.0}$	0.082	4.434
Nanosulfur	$NS_{1.0}$	0.041 (estimated)	2.217
	$NS_{1.5}$	0.062	3.325
	$NS_{2.0}$	0.082	4.434
Sulfuric acid	$SA_{1\%}$	0.124/16 g H_2O (estimated)	6.652
	$SA_{3\%}$	0.124/15.65g H_2O	6.652
	$SA_{5\%}$	0.124/15.31g H_2O	6.652
Leaching with water		150 ml	

The laboratory experiment lasted for 60 days, and four blocks of the experimental scheme were used to assess the ameliorative efficiency of different doses and incubation periods of the ameliorants. After 15, 30, and 60 days of incubation, each block was eliminated, and the ionic composition (HCO_3^-, CO_3^{2-}, Cl^-, SO_4^{2-}, Ca^{2+}, Mg^{2+}, Na^+, K^+), total salts, and pH of the water extract from the soils were determined (USDA, 2014; 2022). The experiment was replicated three times. 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 version 4.3.0.

Results and Discussion

The laboratory experiment aimed to evaluate the effectiveness of different ameliorants, including phosphogypsum, elemental sulfur (both powdered and nano), and sulfuric acid, on saline-sodic soils in the foothill plain of Ile Alatau. The soil samples, taken from semi-hydromorphic heavy loamy solonetzes, were subjected to various doses and incubation periods of the ameliorants. The analysis of the soil solution emphasized the presence of bicarbonate (HCO_3^-), carbonate (CO_3^{2-}), sulfate (SO_4^{2-}), calcium (Ca^{2+}), and sodium (Na^+) ions (Table 2).

Table 2. Effect of equivalent doses of phosphogypsum, sulfur, nanosulfur, and sulfuric acid on the salt regime of saline-sodic soils

	Days after leaching		Total Salt, %	HCO_3^-, me 100g^{-1}	CO_3^{2-}, me 100g^{-1}	Cl^-, me 100g^{-1}	SO_4^{2-}, me 100g^{-1}	Ca^{2+}, me 100g^{-1}	Mg^{2+}, me 100g^{-1}	Na^+, me 100g^{-1}	K^+, me 100g^{-1}	pH
		Control	0.48±0.066ef	0.86±0.093a	0.17±0.071a	0.11±0.035bc	5.64±0.093fg	0.41±0.035d	0.51±0.012bc	5.43±0.084cd	0.26±0.031cdef	9,25
Phosphogypsum	15 days	PG_1	0.56±0.019cd	0.67±0.018abc	0.13±0.036ab	0.12±0.018bc	7.07±0.287bcd	0.82±0.218bcd	0.46±0.044bc	6.26±0.001b	0.32±0.022b	8,03
		$PG_{1.5}$	0.51±0.009def	0.61±0.018bc	0.16±0.001ab	0.10±0.018c	6.38±0.122def	0.82±0.151bcd	0.42±0.044c	5.54±0.001cd	0.31±0.013bcd	8,06
		PG_2	0.57±0.03cd	0.59±0.040bc	0.09±0.020ab	0.08±0.020c	7.32±0.500bcd	1.08±0.200bc	0.56±0.090bc	6.02±0.320bc	0.33±0.010b	7,96
	30 days	PG_1	0.46±0.024fg	0.68±0.027abc	0.11±0.036ab	0.10±0.0108c	5.64±0.327fg	0.52±0.044cd	0.52±0.044bc	5.08±0.378d	0.29±0.004bcdef	8,08
		$PG_{1.5}$	0.48±0.024efg	0.64±0.00abc	0.11±0.036ab	0.11±0.001bc	5.88±0.336efg	0.78±0.064bcd	0.46±0.044bc	5.08±0.378d	0.31±0.004bcde	8,02
		PG_2	0.53±0.010de	0.59±0.020bc	0.11±0.040ab	0.10±0.040c	6.76±0.160cde	0.91±0.090bcd	0.56±0.110bc	5.65±0.001cd	0.32±0.001b	7,97
	60 days	PG_1	0.62±0.012bc	0.76±0.080abc	0.13±0.036ab	0.21±0.0108a	7.61±0.198bc	0.57±0.111bcd	0.46±0.044bc	7.22±0.276a	0.33±0.018b	8,18
		$PG_{1.5}$	0.64±0.016b	0.72±0.027abc	0.16±0.001ab	0.17±0.040ab	8.03±0.178b	0.67±0.111bcd	0.69±0.067ab	7.22±0.276a	0.34±0.018b	8,18
		PG_2	0.73±0.020a	0.59±0.040bc	0.08±0.001bc	0.14±0.020abc	9.62±0.320a	1.83±0.310a	0.86±0.110a	7.22±0.280a	0.42±0.001a	7,99
	After 60 days	PG_1	0.28±0.017h	0.79±0.222ab	0.11±0.036ab	0.08±0.0108c	2.96±0.356g	0.40±0.133d	0.46±0.044bc	2.73±0.276f	0.24±0.044	8,05
		$PG_{1.5}$	0.34±0.005h	0.77±0.044abc	0.08±0.001bc	0.07±0.001c	3.84±0.129h	0.47±0.044d	0.42±0.044c	3.55±0.001ef	0.25±0.018	8,02
		PG_2	0.41±0.010g	0.53±0.020c	0.00±0.001c	0.10±0.020c	5.17±0.110g	1.10±0.200b	0.62±0.11abc	3.76±0.001e	0.32±0.00bc	7,84
Sulfur	15 days	$S_{1.0}$	0.52±0.016def	0.63±0.036b	0.16±0.001ab	0.11±0.001ab	6.46±0.184efg	0.65±0.109de	0.46±0.044d	5.78±0.320bcd	0.31±0.011ef	8,03
		$S_{1.5}$	0.62±0.032bcd	0.59±0.044bcd	0.11±0.036abc	0.08±0.018ab	8.02±0.393cde	0.69±0.131de	0.42±0.089d	7.22±0.640ab	0.36±0.018cd	8,05
		$S_{2.0}$	0.73±0.038abc	0.51±0.036cdef	0.11±0.036abc	0.11±0.027ab	9.69±0.600abc	1.44±0.304cde	0.75±0.28bcd	7.70±0.001a	0.42±0.02ab	7,87
	30 days	$S_{1.0}$	0.71±0.017abc	0.47±0.018ef	0.00±0.001d	0.14±0.036a	9.58±0.227abc	1.93±0.089ab	1.40±0.173a	6.50±0.001abc	0.35±0.007cd	7,86
		$S_{1.5}$	0.62±0.024cd	0.48±0.001def	0.08±0.001bcd	0.08±0.018ab	8.23±0.340bcd	1.30±0.044bcd	1.20±0.044ab	5.93±0.378abcd	0.34±0.004de	7,86
		$S_{2.0}$	0.56±0.030de	0.57±0.018def	0.11±0.036abc	0.08±0.018ab	7.21±0.442def	0.95±0.044cde	0.65±0.109cd	5.93±0.378abcd	0.33±0.004def	7,91
	60 days	$S_{1.0}$	0.71±0.032abc	0.60±0.027ef	0.08±0.001bcd	0.15±0.024a	9.26±0.502abc	1.23±0.178bcde	1.15±0.173ab	7.22±0.276ab	0.39±0.013bc	8,01
		$S_{1.5}$	0.74±0.026ab	0.52±0.053f	0.03±0.036cd	0.14±0.018a	9.90±0.373ab	1.80±0.333bc	1.12±0.151abc	7.22±0.276ab	0.41±0.011ab	7,91
		$S_{2.0}$	0.81±0.020a	0.45±0.018f	0.00±0.001d	0.14±0.018a	10.92±0.298a	2.73±0.489a	1.12±0.107abc	7.22±0.276ab	0.44±0.004a	7,79
	After 60 days	$S_{1.0}$	0.43±0.003f	0.59±0.044bcd	0.03±0.036cd	0.08±0.018ab	5.39±0.124g	0.67±0.222de	0.52±0.111d	4.58±0.271d	0.29±0.016fg	7,90
		$S_{1.5}$	0.47±0.039ef	0.53±0.018bcdef	0.00±0.001d	0.08±0.018ab	5.97±0.538fg	1.43±0.378bcd	0.66±0.111cd	4.17±0.818d	0.32±0.004def	7,79
		$S_{2.0}$	0.62±0.081bcd	0.52±0.027bcdef	0.07±0.018cd	0.06±0.013b	8.29±1.131bcd	1.97±0.111ab	1.22±0.084ab	5.33±1.196cd	0.36±0.016cd	7,73
Nanosulfur	15 days	$NS_{1.0}$	0.5±0.022bc	0.83±0.018a	0.19±0.036a	0.10±0.018abc	6.04±0.351ab	0.36±0.107	0.29±0.064cd	6.02±0.320abc	0.29±0.004ab	8,24
		$NS_{1.5}$	0.49±0.020c	0.84±0.053a	0.21±0.036a	0.07±0.001bc	5.90±0.331b	0.39±0.001	0.36±0.089bcd	5.78±0.320abc	0.29±0.004abc	8,26
		$NS_{2.0}$	0.52±0.009abc	0.81±0.071a	0.19±0.036a	0.10±0.036abc	6.24±0.227ab	0.39±0.067	0.20±0.064cd	6.26±0.001abc	0.30±0.013ab	8,26
	30 days	$NS_{1.0}$	0.44±0.026cde	0.84±0.053a	0.16±0.001a	0.07±0.024bc	5.13±0.347bc	0.32±0.044	0.39±0.00abcd	5.08±0.378cde	0.24±0.016bcd	8,30
		$NS_{1.5}$	0.47±0.021c	0.75±0.098a	0.19±0.071a	0.08±0.018bc	5.63±0.271b	0.42±0.089	0.42±0.089abcd	5.37±0.378c	0.25±0.016bcd	8,21
		$NS_{2.0}$	0.46±0.025c	0.80±0.053a	0.24±0.001a	0.08±0.018bc	5.48±0.278bc	0.39±0.067	0.36±0.044bcd	5.37±0.378c	0.24±0.013bcd	8,26
	60 days	$NS_{1.0}$	0.61±0.034a	0.67±0.120a	0.19±0.036a	0.12±0.018ab	7.64±0.567a	0.57±0.089	0.62±0.111ab	7.02±0.276a	0.33±0.027a	8,24
		$NS_{1.5}$	0.6±0.003ab	0.65±0.044a	0.16±0.001a	0.13±0.042ab	7.62±0.062a	0.60±0.067	0.66±0.044a	6.81±0.001ab	0.34±0.016a	8,14
		$NS_{2.0}$	0.6±0.017ab	0.67±0.071a	0.13±0.036a	0.17±0.013a	7.57±0.207a	0.63±0.178	0.62±0.178ab	6.81±0.411ab	0.34±0.022a	8,15
	After 60 days	$NS_{1.0}$	0.35±0.023de	0.81±0.089a	0.16±0.001a	0.06±0.013bc	4.02±0.347c	0.27±0.044	0.49±0.001abc	3.93±0.267de	0.20±0.018d	8,26
		$NS_{1.5}$	0.45±0.074cd	0.75±0.089a	0.19±0.036a	0.07±0.024bc	5.39±1.107bc	0.37±0.111	0.46±0.044	5.13±0.929cd	0.25±0.022bcd	8,22
		$NS_{2.0}$	0.34±0.030de	0.76±0.107a	0.13±0.036a	0.04±0.001c	3.92±0.527c	0.33±0.156	0.42±0.044abcd	3.73±0.267e	0.22±0.029cd	8,29
Sulfuric acid	15 days	$SA_{1\%}$	0.78±0.294abcd	0.56±0.107cde	0.08±0.053bc	0.10±0.018abcd	10.42±4.482abcd	2.71±2.571bc	0.98±0.782cd	6.98±0.960abc	0.41±0.069bcde	7,83
		$SA_{3\%}$	0.81±0.174abcd	0.49±0.062de	0.05±0.092bc	0.07±0.001cd	10.89±2.607abcd	2.65±1.304bc	0.91±0.416cd	7.46±0.800ab	0.44±0.044abcd	7,74
		$SA_{5\%}$	1.08±0.067a	0.45±0.018bcd	0.00±0.001c	0.08±0.018bcd	14.87±1.024a	5.55±0.678ab	1.40±0.282cd	7.94±0.320a	0.51±0.004a	7,62
	30 days	$SA_{1\%}$	0.53±0.020cd	0.65±0.036bcd	0.16±0.001ab	0.10±0.018abcd	6.61±0.236cd	0.56±0.089c	0.59±0.067d	5.93±0.378bcd	0.28±0.009fgh	8,10
		$SA_{3\%}$	0.87±0.017abc	0.41±0.036cd	0.00±0.001c	0.10±0.018abcd	12.05±0.282abc	2.84±0.067abc	2.55±0.262ab	6.78±0.378abcd	0.39±0.001cde	7,73
		$SA_{5\%}$	1.03±0.019a	0.39±0.0108d	0.00±0.001c	0.14±0.036ab	14.56±0.293a	4.31±0.329ab	3.59±0.238a	6.78±0.378abcd	0.40±0.009cde	7,69
	60 days	$SA_{1\%}$	0.64±0.016bcd	0.69±0.062abc	0.16±0.08ab	0.16±0.013a	8.12±0.276bcd	0.63±0.244c	0.99±0.001cd	7.02±0.276abc	0.34±0.027efg	8,19
		$SA_{3\%}$	0.94±0.053ab	0.45±0.036e	0.03±0.046c	0.16±0.013a	12.90±0.784ab	4.13±0.756ab	1.48±0.133bcd	7.43±0.001ab	0.47±0.018abc	7,78
		$SA_{5\%}$	1.09±0.061a	0.44±0.027e	0.00±0.001c	0.10±0.018abcd	15.19±0.909a	6.17±1.111a	1.84±0.240bc	7.22±0.276ab	0.5±0.016ab	7,64
	After 60 days	$SA_{1\%}$	0.45±0.071d	0.81±0.089ab	0.21±0.036a	0.05±0.013cd	5.39±1.091d	0.37±0.089c	0.52±0.111d	5.13±0.929de	0.24±0.022h	8,26
		$SA_{3\%}$	0.54±0.074cd	0.44±0.053e	0.03±0.046bc	0.06±0.015cd	7.18±1.167cd	2.27±0.644bc	1.12±0.151cd	3.93±0.267e	0.34±0.022defg	7,77
		$SA_{5\%}$	0.64±0.054bcd	0.43±0.036e	0.00±0.001c	0.06±0.013d	8.68±0.820bcd	3.10±0.600abc	1.58±0.200bcd	4.13±0.001e	0.36±0.013def	7,72

In terms of phosphogypsum, the 15-day incubation had minimal impact on the soil's salt regime, with a slight decrease in HCO_3^- ions from 0.86 to 0.67-0.59 meq 100g^{-1}. The CO_3^{2-} ions also decreased from 0.17 to 0.16-0.09 meq 100g^{-1}. However, the CO_3^{2-} ion content remained above the toxicity threshold for plants. The introduction of phosphogypsum led to an increase in SO_4^{2-} ions from 5.64 to 7.07-9.62 meq 100g^{-1} and Ca^{2+} ions from 0.41 to 0.57-1.83 meq 100g^{-1}. The Na^+ ion content in the soil solution increased from 5.43 to 7.22 meq 100g^{-1} after 60 days of incubation. Leaching the phosphogypsum-treated soil resulted in decreased SO_4^{2-} and Na^+ ion concentrations compared to the control.

For elemental sulfur, the calculated dose effectively reduced HCO_3^- ions from 0.86 to 0.51 meq 100g^{-1} after 15 days of incubation. CO_3^{2-} ions decreased from 0.17 to 0.11-0.08 meq 100g^{-1}. The SO_4^{2-} ion content increased from 5.64 to 6.46-11.0 meq 100g^{-1}, and Ca^{2+} ions increased from 0.41 to 0.65-2.73 meq 100g^{-1}. Na^+ ions in the soil solution increased from 5.43 to 7.22 meq 100g^{-1}. Leaching the elemental sulfur-treated soil resulted in decreased SO_4^{2-} and Na^+ ion concentrations compared to the incubation period.

Nanosulfur application caused noticeable decreases in HCO_3^- ions from 0.86 to 0.82-0.65 meq 100g^{-1} after 15 to 60 days of incubation. CO_3^{2-}ions decreased to 0.13-0.11 mgE. The SO_4^{2-} ion content increased to an average of 7.5 meq 100g^{-1}, and Ca^{2+} ions increased compared to the control. Leaching did not significantly affect the HCO_3^- and CO_3^{2-} ion content.

Sulfuric acid, particularly at concentrations of 1%, 3%, and 5%, exhibited significant effects on the soil solution. After 15 days of incubation, HCO_3^- ions decreased to 0.45-0.56 meq 100g^{-1}, and CO_3^{2-} ions dropped to 0.00-0.08 meq 100g^{-1}. The SO_4^{2-} ion content increased to 10.42-14.87 meq 100g^{-1}, and Ca^{2+} ions significantly increased compared to the control. Na^+ ions in the soil solution averaged 7.00 meq 100g^{-1} before leaching and decreased to 3.93-5.13 meq 100g^{-1} after leaching. Sulfuric acid effectively neutralized alkalinity, resulting in a rearrangement of the soil's ionic composition.

Overall, sulfuric acid demonstrated the highest effectiveness among the ameliorants, followed by elemental sulfur. Phosphogypsum exhibited the lowest effectiveness in terms of its impact on the soil's ionic composition. The findings highlight the ability of sulfuric acid to neutralize alkalinity, decrease HCO_3^- and CO_3^{2-} ion content, and increase SO_4^{2-} ion concentrations, leading to significant changes in the soil's chemical properties.

These results provide valuable insights into the mechanisms involved in the amelioration of saline-sodic soils and can guide the development of effective soil improvement strategies. However, further research and field studies are necessary to validate these laboratory findings and optimize their practical applications in soil reclamation and management.

The results of the experiment demonstrate that the application of phosphogypsum, elemental sulfur, nanosulfur, and sulfuric acid, as well as their incubation duration, have a significant impact on the ionic composition of the aqueous extract of soda-sulfate soil. This impact is particularly noticeable in the bicarbonate, carbonate, and sulfate ion content throughout the entire incubation period of the ameliorants in soda-sulfate soil. The introduction of ameliorants disrupts the equilibrium state of the soil's ion-salt system, which involves the salts of the solid phases of the soil and the soil absorbing complex. These solid phase components constantly interact with the soil solution and air.

The ionic composition analysis of the water extract from the soda-sulfate soil reveals that the application of phosphogypsum ($CaSO_4 \cdot 2H_2O$) increases the Ca^{2+} and sulfate ion content in the soil solution. Specifically, there is a noticeable difference between the PG2.0 variant and the control. It appears that Ca^{2+} in the soil solution interacts with the soil-absorbing complex (SAC) of the soda-sulfate soil, displacing absorbed sodium into the solution, and introducing Ca^{2+} into the SAC according to the reaction: $2(SAC - Na) + CaSO_4 \rightarrow (SAC - Ca) + 2Na_2SO_4$. This process leads to a significant increase in the displaced sodium content in the solution compared to the control (5.43 meq 100g^{-1}), observed after 60 days of incubation with phosphogypsum (7.4 meq 100g^{-1}). This difference is statistically significant (M=2.0). Since the reaction product is Na_2SO_4, which is readily soluble and toxic to plants, the Na^+ and SO_4^{2-} ion content decreased after leaching to 2.73, 3.55 and 3.75 meq 100g^{-1}, and 2.95, 3.84, and 5.17 meq 100g^{-1}, respectively, compared to the initial values before leaching. Another possible interaction of gypsum is with bicarbonates and sodium carbonates. The chemical reaction between $CaSO_4$ and Na_2CO_3 forms sparingly soluble calcium carbonates according to the equation: $CaSO_4 + Na_2CO_3 \rightarrow CaCO_3 + Na_2SO_4$. Despite noticeable changes, previous studies (Feofarova, 1950) suggest that the introduction of phosphogypsum reduces the initial rate of interaction with the soil on sulfate, especially in soda-alkaline soils, due to the coating of their crystal surfaces with a humus-clay-carbonate film.

The introduction of elemental sulfur powder and nanosulfur into soda-sulfate soil significantly increases the sulfate ion content. After 60 days of incubation, the sulfate ion content reaches 9.32-11.0 meq $100g^{-1}$ for elemental sulfur and 7.6 meq $100g^{-1}$ for nanosulfur, compared to 5.64 meq $100g^{-1}$ in the control. This indicates that a portion of the introduced elemental sulfur gradually transforms into its di- and trioxide forms with the involvement of sulfur-oxidizing microorganisms, following the scheme: $S° \rightarrow SO_2^{2-} \rightarrow SO_3^{2-}$. The trioxide form combines with water ($SO_3 + H_2O \rightarrow H_2SO_4$), resulting in the formation of sulfuric acid, an ideal ameliorant for alkaline soils. The reclamation process, which involves the conversion of alkaline salts (Na_2CO_3 and $NaHCO_3$) into neutral salts (Na_2SO_4, $MgSO_4$, and $CaSO_4$), occurs under mild conditions due to the gradual transformation of sulfur into sulfuric acid. The slight increase (~1.5-2 times) in the concentration of Ca^{2+} and Mg^{2+} ions can be attributed to the decomposition of carbonates during their interaction with the newly formed sulfuric acid, as described by the equation: $CaCO_3 + H_2SO_4 \rightarrow CaSO_4 + H_2CO_3$, resulting in the formation of a more soluble salt ($CaSO_4$ 0.2 g/l) from an insoluble one ($CaCO_3$ 0.02 g/l).

The application of sulfuric acid in the form of 1%, 3%, and 5% solutions induces significant changes in the ionic composition of the liquid phase of the soil. The sulfuric acid solution primarily reacts with the soil's liquid phase, instantaneously neutralizing alkaline sodium salts and converting them into neutral sodium sulfate (which is 10 times less toxic than Na_2CO_3), as shown in the reactions: $Na_2CO_3 + H_2SO_4 \leftrightarrow Na_2SO_4 + H_2O + CO_2\uparrow$ and $2NaHCO_3 + H_2SO_4 \leftrightarrow Na_2SO_4 + H_2CO_3 + H_2O + CO_2\uparrow$. This leads to a substantial decrease in the bicarbonate ion (HCO_3^-) content to 0.38-0.69 meq $100g^{-1}$, compared to 0.86 meq $100g^{-1}$ in the control (M=-0.4), thus reducing its toxicity and completely eliminating normal carbonate (CO_3^{2-}). Additionally, sulfuric acid reacts with carbonates in the solid phase of the soil, mainly calcium carbonate, converting it into a more water-soluble form, secondary subsoil gypsum, through the reaction: $CaCO_3 + H_2SO_4 \leftrightarrow CaSO_4 + H_2O + CO_2\uparrow$. This is supported by the increased sulfate ion content (M = 5.1 and M = 7.7) and calcium ion content (M = 2.6 and M = 4.4) in the solution of the SA3% and SA5% variants, respectively, compared to the control. The newly formed fine-crystalline gypsum dissolves and increases the calcium concentration in the soil solution, leading to a shift in the previously established balance between Ca^{2+} and Na^+. As a result, calcium in the solution helps displace the absorbed sodium from the SAC. Therefore, the most effective ameliorant is found to be the sulfuric acid solution, with increasing concentrations leading to faster attainment of equilibrium state between the pore solution and SAC, which occurs within less than a day. Amezketa et al. (2005) indicated that the addition of sulphuric acid was the most effective treatment in leaching and reducing salinity in comparison with gypsum amendments. However, the application of acidic amendments can lower soil pH, thus, their applications need some consideration.

Conclusion

In conclusion, the laboratory experiment conducted to assess the ameliorative efficiency of phosphogypsum, elemental sulfur, and sulfuric acid on soda-saline soils in the foothill plain of the Northern Tianshan region has provided valuable insights. Among the tested ameliorants, sulfuric acid solution demonstrated the highest effectiveness. Even at a 5% concentration, it was able to completely neutralize normal carbonates in the soil solution, effectively reducing soil alkalinity. The positive impact of sulfuric acid was observed as early as 15 days of incubation in the soda-saline soil. The introduction of sulfuric acid resulted in a significant decrease in bicarbonate and carbonate ion content after 60 days of incubation, while the sulfate ion content increased proportionally to the concentration of sulfuric acid, reaching levels of 8.12, 12.98, and 15.19 meq $100g^{-1}$. This increase in sulfate ions can be attributed to the interaction of sulfuric acid with calcium carbonates in the solid phase of the soil, leading to the formation of subsoil gypsum. The presence of subsoil gypsum facilitates the displacement of absorbed sodium from the soil-absorbing complex (SAC) by calcium ions. Similarly, the introduction of phosphogypsum also resulted in an increase in sodium ion content in the soil solution after 60 days of incubation, indicating the displacement of sodium from SAC by calcium ions.

The application of finely dispersed elemental sulfur in soda-sulfate soil significantly increased the sulfate ion content, reaching 11.0 meq $100g^{-1}$ compared to 5.64 meq $100g^{-1}$ in the control. This increase can be attributed to the oxidation of elemental sulfur to its di- and trioxide forms, with the latter combining with water to form subsoil sulfuric acid. The action of subsoil sulfuric acid is expected to be milder compared to directly introduced sulfuric acid.

The findings of this laboratory experiment contribute to a better understanding of the reclamation processes involved in the treatment of soda-saline alkaline soils. This knowledge provides a theoretical basis for the chemical reclamation of saline-sodic soils, which are prevalent in Kazakhstan and other regions worldwide.

Acknowledgments

We gratefully acknowledge the generous funding provided by the Kazakhstan Science and Education Ministry (Project No. AP13068643), which made this research possible. We would like to express our sincere appreciation to the anonymous reviewers for their constructive comments and insightful contributions, which greatly improved the quality of this article. Their valuable feedback has been instrumental in shaping the final outcome of our study.

References

Amezketa, E., Aragüés, R., Gazol, R., 2005. Efficiency of sulfuric acid, mined gypsum, and two gypsum by-products in soil crusting prevention and sodic soil reclamation. *Agronomy Journal* 97(3): 983–989.

El hasini, S., Halima, I.O., Azzouzi, M.E., Douaik, A., Azim, K., Zouahri, A., 2019. Organic and inorganic remediation of soils affected by salinity in the sebkha of sed el mesjoune – marrakech (Morocco). *Soil and Tillage Research* 193: 153-160.

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.

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.

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.

Rengasamy, P., 2002. Transient salinity and subsoil constraints to dryland farming in Australian sodic soils: an overview. *Australian Journal of Experimental Agriculture* 42(3): 351–361.

Rengasamy, P., 2006 World salinization with emphasis on Australia. Journal of Experimental Botany 57(5): 1017–1023.

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.

Shaygan, M., Baumgartl, T., 2022. Reclamation of Salt-Affected Land: A Review. *Soil Systems* 6(3): 61.

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: 04.11.2022]: 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: 04.11.2022]: https://www.nrcs.usda.gov/sites/default/files/2022-10/SSIR42-v6-pt1.pdf

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.