

Research Article

Effect of Phosphogypsum Amendment on Chemical Properties of Sodic Soils at Different Incubation Periods

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The application of phosphogypsum (PG) on sodic soils provides nutrients to the soil, reduces the toxic effect of Na⁺, and improves soil properties. Laboratory experiments were performed to evaluate the effects of PG on the chemical properties of sodic soils. The treatments were arranged in a completely randomized design with five replications. The treatments included 0% GR (control), 50% GR (28.18 g·kg⁻¹), 100% GR (56.37 g·kg⁻¹), 150% GR (84.50 g·kg⁻¹), and 200% GR (112.74 g·kg⁻¹) rates that were thoroughly mixed with soil under incubation, whereas PG was mixed with topsoil before leaching at the same application rates under the leaching experiment. Soil and leachate samples from each pot were collected in 7, 14, 21, 28, and 35 days and subjected to spectrometric analysis. Results indicated that there was a highly significant (p < 0.001) effect on soil pH, exchangeable sodium percentage (ESP), available *P*, exchangeable Na⁺, and Ca⁺² under 35-day incubation compared with control. In a closed incubation system, most of the nutrients were released after 7 days of incubation and inconstantly released after 14 days of incubation. Furthermore, the removal of Na⁺ and SAR increased in initial leachate collection and decreased with the subsequent application of irrigation water (PV). Because of the high contents of Ca⁺² released from PG and the residual effect of H₂SO₄, soil pH and ESP were rapidly reduced compared with control. Post leachate analysis also revealed that available P and extractable S-SO₄⁻² were significantly (p < 0.001) increased in soil solutions. However, available *P* was decreased during incubations compared with the value of post leachate analysis. During a closed incubation, displaced Na⁺ replaces Ca⁺² on exchange sites, resulting in increased Ca-P precipitation. Thus, the combined application of PG and irrigation water in 7 to 14 days would allow chemical reaction with the soils and reduce sodicity problems to crop planting.

1. Introduction

Soil degradation resulting from sodicity is a major environmental threat to agricultural productivity in arid and semiarid regions [1]. Sodic soils are characterized by high contents of exchangeable Na⁺ and soluble $CO_3^{2^-}$ and HCO_3^- in the soil solutions [2, 3]. It causes the loss of soil's physical structure by clay swelling and dispersion [3]. Dispersed sodic soils are compacted and have a reduced movement of water, air, and solute through the soil profile [4]. The reclamation of sodic soils requires the displacement of Na⁺ from the soil exchange sites by Ca²⁺ to promote soil flocculation [5]. Subsequently, the displaced salts are leached from the soil profile by the application of irrigation water [6]. It provides a special approach to maintaining their productivity and

enhancing crop production in the arid and semiarid regions [7]. Extensive research has been conducted to use chemical amendments to provide Ca^{2+} to replace Na^+ on the exchange sites [8–10]. Gypsum (CaSO₄·2H₂O) is the most commonly used chemical amendment, and its efficiency as a supplier of Ca^{2+} to offset Na^+ on exchange sites has been long studied and is an established technology for the reclaimed sodic soils [5, 11, 12]. However, its slow reaction, high cost of exploitation, transportation, and crushing gypsum have been blamed [13].

Phosphogypsum (PG) is an industrial solid by-product generated during the production of phosphate fertilizers through a wet process, in which apatite reacts with sulfuric acid to produce phosphoric acid [14, 15]. The wet process generates a large amount of PG [16, 17], exceeding 280



FIGURE 1: Location map of the study area.

million tons per year worldwide [18], of which only 14% is revalorized, 28% is dumped into water bodies, and 58% is stockpiled [19]. More than 92% of PG contains $CaSO_4 \cdot 2H_2O$, which is an excellent source of calcium to reclaim sodic soils. The application of PG to sodic soils enhanced nutrient availability to growing crops because of the presence of large amounts of calcium, phosphorus, and sulfate [20–22]. PG is used in agriculture all over the world, for example, in Brazil, Spain, Australia, India, Pakistan, USA, and Egypt [23, 24], either as a soil amendment [25–27] or as a fertilizer [28, 29]. The beneficial effects of PG in agriculture have been reported for ameliorating sodic soils [27] and subsoil acidity [30, 31].

Thus, the utilization of PG has achieved positive results, and the level of overall utilization is increasing year after year. However, the amount of PG application to the sodic soils and the time at which it dissolves and releases the nutrients for the growing plants are not yet identified. Thus, it is crucial to assess the chemical response of soil to PG and the release of plant nutrients at a specific time before recommending its large-scale field application. The objective of the study, therefore, is to determine the effect of phosphogypsum amendment on the chemical properties of sodic soils at different incubation periods.

2. Materials and Methods

2.1. Description of the Study Area. A soil sample was collected from Alage, Central Rift Valley of Ethiopia (Figure 1). The site was located in Tepid semiarid midhighlands (SA3) at 07° 34'59"N and 38° 25'33"E and about 217 km south of Addis Ababa and 38 km west of Bulbula town in the vicinity of Rift Valley lakes (Abidjata and Shalla). It has an elevation of 1600 m.a.s.l, with average annual rainfall ranging from 750–1,171 mm. Average annual temperatures range from 5.1 to 33.6°C. Based on the World Reference Base, the soil of the trial is classified as Solonetz [32]. Initial soil, PG, and irrigation water were analyzed (Table 1).

2.2. Treatments and Experimental Design. Sodic soil used in the incubation experiment was collected from 0-20 cm depth using an auger by the random sampling technique. The collected soil sample was crushed and passed through a 2 mm sieve and placed in plastic pots. The treatments were arranged in a completely randomized design with five replications. The five PG levels (0, 50, 100, 150, and 200% GR) at increasing levels of PG were used. The gypsum requirement of PG amendments (GR_{PG}) was calculated using a modified method of Zhao et al. [33].

TABLE 1: Chemical analysis of soil (0–20 cm depth), irrigation water, and PG used in the study.

Items	Units	Soil	Irrigation water	Phosphogypsum
Sand	%	46.67		_
Silt	%	20.33	_	_
Clay	%	33.00	_	_
Texture	_	Loam	_	_
Bd	g⋅cm ⁻³	0.92	_	_
OM	%	4.44	_	_
pН	_	9.94	7.80	2.26
ĒC	dSm^{-1}	0.33	0.17	8.30
Avai. P	$mg \cdot kg^{-1}$	0.12	_	105.04
Excha. Na	$cmol_c \cdot kg^{-1}$	28.88	_	1.47
Excha. K	$\text{cmol}_{c} \cdot \text{kg}^{-1}$	1.48	_	2.99
Excha. Ca	$\text{cmol}_{c} \cdot \text{kg}^{-1}$	22.01	_	140.49
Excha. Mg	$\text{cmol}_{c} \cdot \text{kg}^{-1}$	1.00	_	1.01
CEC	$\text{cmol}_{c} \cdot \text{kg}^{-1}$	42.00		
ESP	%	68.75	_	_
Fe	$mg \cdot kg^{-1}$	5.02	_	7.10
Zn	$mg \cdot kg^{-1}$	0.29	_	0.11
Mn	$mg \cdot kg^{-1}$	0.69	_	0.94
Cu	$mg \cdot kg^{-1}$	3.00	_	0.04
Na	$mg \cdot kg^{-1}$	_	0.75	_
Κ	$mg \cdot kg^{-1}$	_	0.17	_
Ca	$mg \cdot kg^{-1}$	_	1.00	_
Mg	$mg \cdot kg^{-1}$	_	1.22	_
SAR	_	_	0.71	_
SO_4^{-2}	meq L ⁻¹ , PG/mg·kg ⁻¹	6.08	0.04	1856.14
PO_4^{-3}	$meq L^{-1}$	_	2.00	_
Cl ⁻	$meq L^{-1}$	17.51	0.28	_
HCO ₃ ⁻	meq L ⁻¹	100.39	2.00	_
CO_3^{-2}	meq^{-1}	25.13	_	_
RSC	$meq L^{-1}$	_	-0.22	

Excha = exchangeable; SAR = sodium adsorption ratio; Bd = bulk density; $EC_w = electrical$ conductivity of water; RSC = residual sodium carbonate; ESP = exchangeable sodium percentage.

$$GR_{PG}(KG/ha) = [86 \times CEC \times (ESP - 10\%) + 86 \times TA - 28.22] \times d \times B \ d \times \eta/f,$$
(1)

where GR_{PG} is the gypsum requirement of PG amendments (kg ha⁻¹), ESP is the exchangeable sodium percentage (%), CEC is the total cation exchange capacity (cmol_c·kg⁻¹), TA is the total alkalinity (CO₃⁻² + HCO₃⁻, mg kg⁻¹), *d* is the soil depth to be reclaimed in cm, which is 20 cm in this study, *Bd* is the bulk density (g·cm⁻³), *f* is the effective utilization of CaSO₄ (100%), and η is the CaSO₄ content of the PG (65–70%), which is 65% in this study.

2.3. Incubation Experiment. For each treatment, 800 g of airdried (<2 mm) soil was thoroughly mixed with different rates of PG and transferred into plastic bottles with an internal diameter of 10 cm and 30 cm in height, in a closed system. The treated soil was kept for 35-days at room temperature (25° C) and distilled water was added to bring the soil to field capacity moisture content (29.89%). Soil samples were collected periodically (0, 7, 14, 21, 28, and 35 days of incubation) from the plastic pots and analyzed for selected chemical properties to assess the effect of increasing levels of PG amendment on sodic soils.

2.4. Leaching Experiment. The leaching experiments were also carried out in plastic bottles with an internal diameter of 7 cm and 10 cm in height. The bottom of each plastic bottle was filled with a sand (0.5 cm) layer to facilitate leaching. Then, 200 g of air-dried (<2 mm) soil sample was added with a small increment to obtain a uniform bulk density. The soil was packed to a height of 6 cm, making the soil depth 6.5 cm in each pot, and storage bottles were also placed below each pot to collect the leachate. The PG treatments were mixed with the upper 1 cm of the soil column before leaching at the rates of 0, 50, 100, 150, and 200% GR. Irrigation water from the Djido river, the Alage irrigation canal, was used for leaching. Four pore volumes (PV) of irrigation water were allowed to pass through the soil column and leachates were collected for every pore volume. The PV is the volume of water required to saturate all soil pores from the bottom to remove any air pockets developed during the packing process. The collected leachates were centrifuged and analyzed for Na⁺, Ca⁺², and Mg⁺². After the completion of the leaching phase, soils from all columns were carefully removed, air-dried, crushed to pass through a 2 mm sieve, and analyzed for pH, Na⁺, K⁺, Ca⁺², Mg⁺², S-SO₄⁻², and available P following standard laboratory procedures. The value of sodium adsorption ratio (SAR) was computed as follows:

SAR =
$$\frac{[Na^+]}{\sqrt{\frac{1}{2}([Ca^{+2}] + [Mg^{+2}])}}$$
 (2)

2.5. Laboratory Analyses of the Soil Samples. Soil pH was measured using a glass combination electrode inserted in the filtered supernatant solution prepared by 1:2.5 soil to water ratio [34]. Available phosphorous was extracted using the Olsen method [35]. The extracted solution was filtered through Whatman filter paper No. 42 and P contents were determined using the Molybdate blue color method using a UV-Visible Spectrophotometer at 880 nm wavelength. The sulfate contents were extracted with 0.15% CaCl₂.2H₂O, and S-SO₄⁻²contents were determined by a turbidimetric procedure using UV-Visible Spectrophotometer (SKU: S-2150UV) at 470 nm wavelength [36]. Exchangeable cations (K⁺, Ca⁺², Mg⁺² and Na⁺) were extracted with 1 M ammonium acetate (NH₄OAc) at pH 7.0 [37]. The concentrations of Ca^{+2} and Mg^{+2} were measured using atomic absorption spectrometry, while K⁺ and Na⁺ were measured using flame spectrophotometry. The cation exchange capacity (CEC) of the soil was estimated by measuring the sum of exchangeable cations from the NH₄OAc extracted sample [38]. The value of exchangeable sodium percentage (ESP) was computed as follows:

$$ESP = \frac{Exchangeable Na}{CEC} \times 100.$$
 (3)

2.6. Irrigation Water Analysis. Irrigation water from the Djido River, Alage irrigation canal, was collected and analyzed for EC_w, pH, Ca⁺², Mg⁺², Na⁺, K⁺, SAR, PO₄⁻³, CO₃⁻², SO₄⁻², HCO₃⁻, and Cl⁻ following the methods developed in USLS [34]. The residual sodium carbonate (RSC) content of the irrigation water was calculated as RSC = (HCO₃⁻ + CO₃⁻²) – (Ca⁺² + Mg⁺²).

2.7. Statistical Analysis. Before the analysis of variance (ANOVA), the normality of the data was checked using the Shapiro-Wilk normality test. Significant differences between the means were determined using Fisher's protected LSD (p < 0.05) test. Pearson's correlation coefficients (r) were performed using statistical analysis systems (SAS) software 9.3 [39].

3. Results

3.1. Initial Soil, Irrigation Water, and PG Analysis. The chemical analysis of the irrigation water, PG, and soil used for the study was analyzed before starting the experiment (Table 1). Results revealed that the soil of the study area is strongly classified as sodic soil with high soil pH, high ESP, low OM, and low available *P*. Similar results were observed by Alemayehu et al. [32]. The high levels of ESP and soil pH are inherent limitations to crop production in the study area. The main sources for the sodic soils of the studied area developed from lacustrine deposits of Lake Shalla. Irrigation water from the Djido river analysis revealed that it is low in

salinity hazard ($EC_w = 0.168 \text{ dS} \cdot \text{m}^{-1}$), low in sodicity hazard (SAR = 0.75 meq·L⁻¹), and safe in RSC hazard (-0.22 meq·L⁻¹), with moderately alkaline pH (7.8) [40]. As a result, Djido river irrigation water is considered safe for irrigation purposes. It showed that the Djido river irrigation water is not the main cause of sodic soils in the study area.

The PG material used for this study had high amounts of exchangeable Ca^{+2} (140.49 cmol_c·kg⁻¹), Fe (7.1 mg·kg⁻¹), SO₄⁻² (1856.14 mg·kg⁻¹), P (105.04 mg·kg⁻¹), and ECe (8.3 dS·m⁻¹) with low pH (2.26) values, indicating that PG is suitable for application on sodic soils as reclaiming materials and can be used as fertilizer requirements for growing crops, particularly *S* and *P*. Similar results were observed by different authors [17, 41]. Very low pH and high soluble Ca^{+2} contents of PG are expected to acidify sodic soils, reduce soil pH, and easily alleviate the sodicity effect in a quick time [27, 42, 43].

3.2. Effect of PG Amendment on Chemical Properties of Sodic Soil under Incubation

3.2.1. Soil pH. Soil pH was significantly (p < 0.001) reduced with increasing PG level compared with control (Table 2). The PG level, incubation time, and their interactions had higher significant (p < 0.001) effects on soil pH. Results revealed that soil pH rapidly decreased from 9.39 (control) to 7.65 (200% GR) in 7 days of incubation. The improvement of soil pH was observed after 7 days of incubation and continued its reduction to 14 days and rise to 21 days for some of the treatments (Table 2). The PG used in this study released a large amount of soluble Ca^{+2} and SO_4^{-2} into the soil and displaced Na⁺, HCO₃⁻, and CO₃⁻² from the exchangeable site [33, 44]. This fast chemical reaction changes sodic salt into neutral salt and makes its soil pH below 8.5 [45]. The residual effect of sulfuric acids and phosphoric acid in PG also acidifies sodic soils, resulting in soil pH being easily reduced [17, 46]. However, after 21 days of incubation, inconstant soil pH reduction was observed in all PG levels. The inconstant reductions of soil pH after 21 days were attributed to the competition effect of displaced Na⁺ and fixed Ca⁺² in a closed incubation system, which causes the resodification problem in soil solutions. Thus, these studies showed that PG amendments released a huge amount of soluble Ca₊₂ and residual sulfate into the soil solution, which improves consistent soil pH reduction should apply irrigation water to leach excess sodium salt from the system.

3.2.2. Soil ESP. The PG level, incubation time, and their interactions had higher significant (p < 0.001) effects on ESP compared with control (Table 2). All treatments showed an inconstant reduction of ESP with increasing time of incubation. Results revealed that ESP rapidly decrease from 28.82 (control) to 7.82 (200% GR) in 7 days of incubation. The improvement of ESP was observed after 7 days of incubation and rose after 14 days for some of the treatments, and after 14 days of incubation, it showed inconstant reduction (Table 2). The PG released a high content of Ca⁺² into the soil solutions and displaced exchangeable Na⁺ from the

GR (%)	IP (day)	pН	Avail. P	Na	К	Ca	Mg	ESP
0	7	9.39 ^a	2.24 ⁱ	8.52 ^a	1.03 ^{bc}	18.03 ^{ghijkl}	2.18 ^f	28.82 ^{cd}
	14	9.20^{b}	2.35 ⁱ	8.52 ^a	1.03 ^b	13.96 ^{lm}	2.53 ^{ab}	32.80 ^{ab}
	21	9.22 ^b	2.59 ⁱ	8.56 ^a	1.07^{a}	14.16^{klm}	2.62 ^a	32.58 ^{ab}
	28	9.27^{ab}	2.21 ⁱ	8.5 ^a	1.07^{a}	12.98 ^m	2.62 ^a	34.91 ^a
	35	9.31 ^{ab}	2.19 ⁱ	8.51 ^a	1.07^{a}	15.19 ^{jklm}	2.62 ^a	31.06 ^{bc}
	Mean	9.39 ^a	2.32 ^e	8.53 ^a	14.86 ^d	1.06 ^a	2.51 ^a	32.03 ^a
	7	8.35 ^d	3.47 ^{gh}	7.46 ^b	1.03 ^{bc}	20.90 ^{efgh}	2.03 ^g	23.94 ^{fg}
	14	8.32 ^d	3.58 ^{gh}	7.46 ^b	1.03 ^{bc}	16.40 ^{ijklm}	2.55 ^{ab}	27.67 ^{de}
50	21	8.74 ^c	3.51 ^{gh}	7.45 ^b	1.07^{a}	18.37 ^{ghijk}	2.62 ^a	25.36 ^{ef}
50	28	8.59 ^c	3.47 ^{gh}	7.47 ^b	1.07^{a}	16.93 ^{hijklm}	2.62 ^a	26.97 ^{de}
	35	8.65 ^c	$3.32^{\rm h}$	7.48^{b}	1.07^{a}	23.74 ^{cdef}	2.62 ^a	21.42 ^g
	Mean	8.53 ^b	3.47 ^d	7.47 ^b	19.27 ^c	1.06 ^a	2.49 ^{ab}	25.07 ^b
	7	7.91 ^{ef}	4.45^{f}	5.53 ^c	1.0732^{a}	24.89 ^{bcde}	2.21 ^f	16.56 ^h
	14	7.69 ^{ghi}	4.49 ^{ef}	4.73 ^e	1.03 ^{bc}	26.60 ^{bc}	2.48 ^{bc}	13.63 ^{ijk}
100	21	7.95 ^e	4.49 ^{ef}	5.33 ^d	1.03 ^c	19.87 ^{fghi}	2.50 ^{abc}	22.78^{fg}
100	28	7.92 ^{ef}	4.33 ^f	4.53 ^f	1.07^{a}	21.07 ^{defgh}	2.50 ^{abc}	15.53 ^{hi}
	35	7.83 ^{efg}	4.07^{fg}	4.51 ^f	1.07^{a}	20.11 ^{fghi}	2.50 ^{abc}	15.53 ^{hi}
	Mean	7.86 ^c	4.37 ^c	4.93 ^c	22.51 ^{ab}	1.06 ^a	2.44 ^b	16.90 ^c
	7	7.68 ^{ghij}	5.49 ^d	3.46 ^g	1.03 ^{bc}	28.14^{b}	2.28 ^{ef}	10.09 ^{lm}
	14	7.36 ^{lmn}	5.32 ^d	3.46 ^g	1.03 ^c	25.13 ^{bcd}	2.39 ^{cde}	10.90^{kl}
150	21	7.75 ^{fgh}	5.56 ^d	3.47 ^g	1.07^{a}	17.86 ^{ghijkl}	2.39 ^{cde}	14.02 ^{hij}
150	28	7.55 ^{ijk}	5.73 ^d	3.47 ^g	1.07^{a}	19.52^{ghi}	2.39 ^{cde}	13.49 ^{ijk}
	35	7.51 ^{jkl}	5.16 ^{de}	5.48 ^g	1.07^{a}	18.12 ^{ghijkl}	2.39 ^{cde}	13.87 ^{hij}
	Mean	7.57^{d}	5.45 ^b	3.47^{d}	21.75 ^b	1.06 ^a	2.37 ^c	12.48 ^d
	7	7.65 ^{hij}	8.36 ^{ab}	2.96 ^h	1.03 ^{bc}	33.33 ^a	2.35 ^{de}	7.82 ^m
	14	7.40^{klm}	8.64 ^a	$2.97^{\rm h}$	1.03 ^c	21.87 ^{defg}	2.46 ^{bcd}	10.44^{lm}
200	21	7.4^{klm}	7.98 ^{bc}	$2.97^{\rm h}$	1.07^{a}	24.75 ^{bcde}	2.50 ^{abc}	9.49^{lm}
200	28	7.29 ^{mn}	8.63 ^a	$2.97^{\rm h}$	1.07^{a}	18.73 ^{ghij}	2.50 ^{abc}	11.91 ^{jkl}
	35	7.22 ⁿ	7.68 ^c	2.98 ^h	1.07^{a}	21.75 ^{defg}	$2.50^{\rm abc}$	10.51^{lm}
	Mean	7.39 ^e	8.26 ^a	2.97 ^e	24.09 ^a	1.06 ^a	2.46 ^{ab}	10.04 ^e
Treatments	(T)	* * *	* * *	***	ns	***	***	* * *
IP		* * *	* * *	* * *	***	***	* * *	***
T * IP		* * *	ns	* * *	ns	* * *	* * *	* * *
CV (%)		1.61	9.43	2.51	0.11	16.39	4.06	11.78
LSD _{0.05}		0.17	0.26	0.17	0.01	4.22	0.13	2.86

*, **, **, and ns means significant at p < 0.05, p < 0.01, p < 0.001, and not significant at (p < 0.05). CV is the coefficient of variation. The same letter within the column indicates no significant difference at p < 0.05. LSD is the least significant difference, and IP is the incubation period.

exchange sites [47], thereby improving water movement throughout the soil [41]. The greater displacement of the exchanged Na⁺ increased ESP reduction. Our results confirmed the previous finding [27, 42, 43]. The inconstant reduction of ESP in a closed incubation system is because of ion competition between displaced and fixed Ca⁺² in soil solutions. Thus, to ensure effective reclamation, soluble sodium sulfate should be leached and removed from the system. Wang et al. [45] revealed that during the reclamation of sodic soils, displaced sodium salts were constantly leached from the soil. Also, Chaganti et al. [11] pointed out that the leaching of gypsum-treated sodic soils is paramount to ensure the reduction of the sodicity effect.

3.2.3. Exchangeable Cations (Ca^{2+} , Mg^{2+} , K^+ , and Na^+). The PG level, incubation time, and their interactions had higher significant (p < 0.001) effects on exchangeable Ca^{+2} , Na⁺, and Mg⁺², whereas exchangeable K⁺ had no significant (p < 0.05) effect on the PG level and their interaction (Table 2). Results revealed that exchangeable Na⁺ was

reduced from 8.53 to $2.97 \text{ cmol}_c \cdot \text{kg}^{-1}$ after 7 days and slightly reduced until at 14 days incubation. It is because of an increase in the concentration of Ca⁺² from 14.86 to 24.09 $\text{cmol}_{c}\cdot\text{kg}^{-1}$ after 7 days, and it showed a slight reduction after 14 days of incubation. An increase in Ca⁺² concentration after PG application was observed in previous findings [47–49]. The reduction of exchangeable Na⁺ alleviates the toxicity effects of Na⁺ on plant growth [33]. However, the inconstant increment was observed over 14 days of incubation because of the competition of soluble Na⁺ in soil solutions during a closed incubation system. After PG application, no significant (p < 0.05) change was observed on exchangeable Mg^{+2} and K^+ during incubations (Table 2). Very low contents of Mg^{+2} and K^+ in PG and initial soil were used for the study (Table 1) delay significant change in the level of Mg⁺² and K⁺ in PG-treated sodic soils. Also, competing for the same adsorption sites, the high Ca⁺² content induces the reduction of exchangeable Mg^{+2} and K^+ in PG-treated soils [50, 51]. A slight reduction of exchangeable Mg^{+2} after PG application is because of displaced Ca⁺² then leaching out [49].

				1	e		
	pН	Р	Na	К	Ca	Mg	ESP
pН	1.00						
P	-0.54^{**}	1.00					
Na	0.95**	-0.56^{**}	1.00				
Κ	0.04	0.15	-0.0081	1.00			
Ca	-0.52**	0.097	-0.53**	-0.36**	1.00		
Mg	0.21*	0.09	0.19	0.53**	-0.29**	1.00	
ESP	0.91**	-0.48^{**}	0.94**	0.10	-0.73**	0.26	1.00

TABLE 3: Correlation coefficients (r) among different soil parameters during incubation.

** and * means significant at p < 0.01 and p < 0.05 (one-tailed Pearson correlation), respectively.

3.2.4. Available P. Soil available P showed significant (p < 0.001) effects on the PG level, whereas it showed no significant (p < 0.05) effect on the incubation period (Table 2). Results showed that soil available P was increased by 28.09, 42.01, 52.91, and 65.98% over 0, 50, 100, and 150% GR, respectively, during incubation. The soil available P was increased from 2.32 to 8.26 mg·kg⁻¹ with the increasing PG level, however, it shows an inconsistent trend during the incubation period. The relatively highest value of available P was observed after 14 to 21 days of incubation, and the lowest value was observed after 35 days of incubation. The PGtreated soil was saturated by water until 14 to 21 days of incubations, largely increasing the solubility of Ca-P, however, after these stages, water content was decreased, which enhanced the reduction of available P. Our results confirmed that soil available P was significantly increased under saturated water soil condition compared with dry soils [52]. The main reason is because of the increase in soluble phosphates under waterlogging soil than in dry soil conditions. Several findings were reported that PG applications improve the available P in the soil solution over control [17, 53, 54]. PG is a rich source of P, and the faster release of P at the early stage of incubation might be because of the minimal exposure of the released P to the fixation.

The Pearson correlation analysis (*r*) of soil chemical properties during incubation was determined (Table 3). There was positive significant relation between soil pH, ESP ($r=0.91^{**}$), and exchangeable Na⁺ ($r=0.95^{**}$), whereas exchangeable Ca⁺² and available *P* were negatively correlated with exchangeable Na⁺ ($r=-0.53^{**}$) and soil pH ($r=-0.54^{**}$), respectively. It showed that PG amendments were significantly affected by the chemical properties of sodic soils.

3.3. Leachate Analysis

3.3.1. Removal Sodium. The PG level, PV, and their interactions had a higher significant (p < 0.001) effect on the removal of Na⁺ compared with control during irrigation time (Figure 2). Leachate analysis showed that all levels of PG removed most of the displaced Na⁺ during initial collections. The maximum removal of Na⁺ (50.2 mg·L⁻¹) was recorded from the first irrigation step at the highest PG (200% GR) rates, while the lowest value (31.25 mg·L⁻¹) was recorded from the control. Removal of Na⁺ concentration in later collections was decreased because of the depletion of



FIGURE 2: Mean value of cumulative leachate losses of Na at an increasing PG level.

amendment by time, and therefore, it had less impact on Na⁺ concentration. This observation is consistant with that of Gharaibeh et al. [55], who found that Na⁺ concentration significantly dropped with increasing PV irrigation water. Similar results were observed by Gharaibeh et al., [42]. The removal of Na⁺ increased in 2 PV irrigation steps. High Ca⁺² contents released from PG preferentially exchanged Na⁺ and facilitated its release into the soil solution, where it was subsequently leached. Results agree with the closed incubation finding, which states that most of the displaced Na⁺ were removed from the exchange sites after 7 days. Similar observations were made by Yazdanpanah and Mahmoodabadi [56], who found that gypsum application increases the removal of Na⁺ in the leachate. Thus, both incubation and leaching experiments confirmed that the reaction time between the applied PG and sodic soils to displace exchangeable Na⁺ was within 7 days with the subsequent application of irrigation water.

3.3.2. Sodium Adsorption Ratio (SAR). The PG level, PV water, and their interactions had a higher significant (p < 0.001) effect on SAR compared with the control during irrigation time (Figure 3). The maximum SAR was recorded during initial leachate collection. Later, its value decreased with increasing PV, indicating that most of the exchange reactions had taken place at this stage. Results revealed that the maximum value of SAR (24.35 mg·L⁻¹ at 200% GR) was observed at 1 PV compared to control (19.16 mg·L⁻¹), which



FIGURE 3: Mean value of cumulative leachate losses of SAR at an increasing PG level.

gradually decreased with time. After 35 days of the leaching phase, the minimum value of the SAR value $4.14 \text{ mg} \cdot \text{L}^{-1}$ was observed with the highest PG (200% GR), compared with control (19.52 mg·L⁻¹). At the early stages of reclamation, most exchangeable Na⁺ was removed because of decreasing the exchange reaction between Na⁺-Ca⁺², and Na⁺ to Ca⁺ ratio decreased which increased the reduction of SAR. These results agree with the previous finding reported by Shainberg et al. [57] who pointed out that SAR was decreased because of the decreasing exchange reactions between adsorbed Na⁺ and soluble Ca⁺² in soil solutions. A similar report made by Gharaibeh et al. [42] revealed that the maximum value in SAR was recorded at 2 PV. Thus, PG application with adequate irrigation and leaching provided better reclamation of sodic soils in weeks. Thus, our observation showed that fast chemical reactions between Ca⁺² (PG) and soil exchange phases (Na⁺) were observed in 14 days of irrigation time. These findings are similar to those of Ammar et al. [58]. A higher removal of Na⁺ was recorded at first leachate collection. This experiment points out the reaction time between the applied PG and soil colloids before being applied in large-scale fields. Therefore, effective chemical reactions were observed at the 14-day irrigation time. Higher concentrations of Ca⁺² from PG, therefore, improve soil properties and successfully reclaim sodic soils in a short period [59].

3.4. Reclamation Effect of PG Amendments on Sodic Soils. Post leaching soil analysis revealed that soil pH and ESP were significantly reduced (p < 0.001) at the PG level compared with control (Table 4). Results revealed that soil pH and ESP were reduced from 9.35 to 7.28 and 35.60 to 9.38%, respectively, after the leaching of PG-treated soil by 5 PV irrigation steps. The same results of soil pH reduction were observed post and before PG applications. Our experiment revealed the negative linear relationships between the applied PG levels, ESP, and exchangeable N⁺, whereas positive relationships were observed between PG levels and exchangeable Ca⁺² (Figure 4). It indicates a potential effect of PG on the chemical properties of sodic soils. The high

concentration of soluble Ca^{+2} is the best indicator for improving the properties of sodic soils. Thus, the reduction of soil pH and ESP in PG treatments may be attributed to an increase in the level of Ca^{2+} in soil, which promoted Na⁺ displacement and its removal by subsequent leaching.

Post-leaching analysis also revealed that exchangeable Ca^{+2} significantly (p < 0.001) increased in PG level compared with the control (Table 4). Our experiment revealed the positive linear relationships exhibited between available P and applied PG levels (Figure 4). Results showed that the level of exchangeable Ca^{+2} increased from 21.85 cmol_c·kg⁻¹ (control) to 30.33 cmol_c·kg⁻¹ (200% GR). Post-leaching analysis value is similar to the exchangeable Ca⁺² level in 7 days of incubation. It may be because of the leaching effect of exchangeable Na⁺ from the soil solutions. The combined application of gypsum and PV irrigation water increases Na⁺ replacement [42, 60-63], which alleviates the negative effect of Na⁺ on sodic soils [11]. Thus, we concluded that PG amelioration of sodic soils under irrigation effectively and consistently reduced the sodicity effect. However, no significant effect was observed on exchangeable Mg⁺² and K⁺ in the soil after the leaching of 5 PV of irrigation water in the applications of PG level (Table 4). This result agrees with the previous report by Lee et al. [50]. The reduction of exchangeable Mg⁺² is because of replacement by Ca⁺² in PGtreated sodic soils.

Post-leaching soil analysis also revealed that available P and extractable S-SO₄⁻² had a greater significant (p < 0.001) increase in PG level compared with control (Table 4). All PG levels consistently increased the available P and extractable S-SO₄⁻² after the leaching of PG-treated sodic soils. Results show that available P was increased from $7.54 \text{ mg} \cdot \text{kg}^{-1}$ (control) to $28.52 \text{ mg} \cdot \text{kg}^{-1}$ (200% GR) after the leaching of PG-treated sodic soils by 5 PV irrigation water. Our observation confirmed the previous report [17, 53, 54] that P availability increases after the application of PG on sodic soils. Available P content in PG-treated sodic soils after leaching is much higher than the critical value of $10 \text{ mg} \cdot \text{kg}^{-1}$ for some Ethiopian soils [64]. Similarly, extractable S-SO₄ was increased from 12.23 mg kg^{-1} (control) to 78.03 mg kg^{-1} (200% GR) after the leaching of PG-treated sodic soils by 5 PV irrigation water. The very maximum contents of extractable $S-SO_4^{-2}$ were recorded above the critical value of $10-13 \text{ mg} \cdot \text{kg}^{-1}$ for cereal crops [65]. These results confirmed that S-SO₄⁻² levels increased in the soil with PG application [66–68]. High S-SO₄⁻² content in soil solutions replaced HCO_3^{-1} and CO_3^{-2} on adsorption sites and formed soluble sodium sulfate [45]. As the sodium sulfate leached, the sodic level of the soil continuously decreased. Also, the levels of HCO_3^- and CO_3^{-2} rapidly decreased with PG level, reducing the soil pH.

However, different available *P* releases during incubations and post leaching were recorded (Tables 2 and 4). For example, available *P* ranging from 2.32 mg·kg⁻¹ (0% GR) to 8.26 mg·kg⁻¹ (200% GR) was observed during incubation (Table 2), whereas available *P* ranged from 7.54 mg·kg⁻¹ (0% GR) to 28.52 mg·kg⁻¹ (200% GR) after the leaching of PGtreated soils with 5 PV irrigation water was recorded (Table 4). The highest available *P* (8.64 mg·kg⁻¹) released during

GR (%)	nIJ	$S-SO_4^{-2}$	Avail. P	Na	К	Ca	Mg	
	рн	$mg \cdot kg^{-1}$			cmo		ESP %	
0	9.35 ^a	12.23 ^c	7.54 ^e	14.06 ^a	2.33	21.85 ^c	1.23 ^{ab}	35.60 ^a
50	8.47^{b}	13.56 ^c	12.33 ^d	10.17^{b}	2.22	24.79 ^{bc}	1.40^{ab}	26.37 ^b
100	7.87 ^c	68.23 ^b	16.44 ^c	5.88 ^c	2.19	25.29 ^b	1.14^{b}	17.15 ^c
150	7.80 ^c	71.89 ^{ab}	22.75 ^b	4.49 ^{cd}	2.11	28.31 ^a	1.98 ^a	12.13 ^d
200	7.28 ^d	78.03 ^a	28.52 ^a	3.23 ^d	2.04	30.33 ^a	1.53 ^{ab}	9.38 ^d
LSD	0.34	6.18	2.28	1.43	ns	2.95	0.78	3.31
CV	2.29	4.93	7.16	10.45	7.96	6.22	29.51	9.05

TABLE 4: Some selected chemical properties of sodic soils after the leaching of PG amended soils.

ns indicates not significant at p < 0.05.



FIGURE 4: Relationship between chemical properties and application of PG levels after leaching.

the 14-day incubation was much lower than $(28.52 \text{ mg} \cdot \text{kg}^{-1})$ at the highest PG rates. The reduction of available P during incubation was because of its fixation. The PG application increases Na⁺ replacement in a closed incubation system, however, Na⁺ competes with Ca⁺² and is released into soil solutions. The displaced Ca^{+2} reacted with P, reducing P availability [69] compared with post leachate analysis. Competitive exchange reactions between displaced Na⁺ and fixed Ca⁺² in a closed incubation system favor fixations because of the absence of the leaching of displaced Na⁺ in soil solutions [42]. Our results agree with the previous finding [17, 54, 70]. Divalent HPO₄⁻² and Ca⁺² ions competition in closed incubation also promotes Ca-P precipitation [71]. An increase in the available P post leachate analysis, however, was because of the competition of divalent ions (HPO₄⁻² and CO₃⁻²) with Ca⁺², and it forms CaCO₃ [72]. A strong positive relationship indicates that the application of PG on sodic soils caused the enrichment of available soil P and released adequate P to boost fertilizer requirements for growing crops.

4. Conclusions

The PG used in this study positively affects the chemical properties of sodic soils during incubation and after being leached at different periods. The application of PG decreases soil pH and ESP, whereas it increases exchangeable Ca⁺², extractable S-SO₄⁻², and available *P* in sodic soils compared with untreated soils. In a closed incubation system, plant nutrients released from PG-treated soils vary during incubation, and most of the nutrients are released after 7 days of incubation. Furthermore, most of the exchangeable Na⁺ was removed after the leaching of PG-treated sodic soils at first irrigation. Generally, PG application on sodic soils increases plant nutrients and reduces the sodicity level. After the application of combined PG and irrigation water, 7 to 14 days of incubation would allow effective chemical reaction within the soil, which is enough for crop planting. To ensure effective reclamation and keep in view the promise of PG amendments on sodic soils, therefore, laboratory experiments should be repeated in a field.

Data Availability

All data supporting the results of this study are included in this manuscript and if any further information is needed, it will be submitted upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

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