



Comparative evaluation of gypsum amendments for sodic soil reclamation: Solubility, calcium release, hydraulic conductivity and sodium release dynamics

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ABSTRACT

Gypsum amendments are widely used for the reclamation of sodic soils because of their ability to supply calcium and facilitate the displacement of exchangeable sodium. However, the dissolution behaviour and calcium-release capacity of gypsum can vary considerably depending on its source and processing history. The present study evaluated five gypsum materials, namely pure gypsum (G), phosphogypsum (PG), unwashed marine gypsum (MG-UW), field gypsum (FG), and washed marine gypsum (MG-W), to assess their dissolution behaviour, calcium release, and chemical purity, and to examine their effects on hydraulic conductivity and Na^+ concentration in three salt-affected soils (Sitamai, Khanda, and Shivri). Under standardized dissolution conditions, the quantity dissolved ranged from 1.56 to 3.15 g L⁻¹, with G showing the highest value (3.15 g L⁻¹), followed by PG (3.02 g L⁻¹), MG-UW (2.65 g L⁻¹), FG (2.19 g L⁻¹), and MG-W (1.56 g L⁻¹). Calcium release also differed among amendments, ranging from 20.4 to 32.6 meq L⁻¹, with G and MG-UW showing the highest values. Chemical purity ranged from 51.0 to 81.5%, with G and MG-UW exhibiting the highest purity. The soil-column experiment showed distinct responses of hydraulic conductivity and Na^+ concentration to gypsum amendments across Sitamai, Khanda, and Shivri soils, indicating that amendment performance was influenced by both gypsum characteristics and initial soil properties. Overall, the results demonstrate that gypsum source and processing significantly influence dissolution and calcium availability, while soil-specific characteristics determine the subsequent hydraulic and sodium-related responses. Evaluation of gypsum quality based on dissolution, calcium release, and purity, together with site-specific soil properties, is therefore important for selecting appropriate amendments for sodic soil reclamation.

Keywords: Gypsum amendments, Sodic soil, Gypsum dissolution, Calcium release, Chemical purity, Hydraulic conductivity, Phosphogypsum, Marine gypsum, Soil reclamation

INTRODUCTION

The degradation of agricultural land caused by salinity and sodicity represents a major global challenge to food security and sustainable soil management. The latest global assessment by the Food and Agriculture Organization (FAO) estimates

that approximately 1381 billion hectares (Mha) of land, equivalent to 10.7% of the total global land area, are affected by salt-related soil degradation, with particularly extensive occurrence in arid and semi-arid regions where high evaporative demand, inadequate irrigation and drainage, and limited

precipitation promote the accumulation of soluble salts and exchangeable sodium in soils (Qadir *et al.*, 2024; FAO, 2024). The assessment further indicates that approximately 10% of both irrigated and rainfed cropland is affected by salinity, highlighting the substantial implications of salt-affected soils for agricultural productivity and food security (FAO, 2024). In sodic soils, excessive accumulation of Na^+ on soil cation exchange sites promotes clay dispersion, resulting in deterioration of soil structure, reduced hydraulic conductivity and infiltration, and restricted root penetration (Bhardwaj *et al.*, 2009, 2019). These adverse changes in soil physical conditions ultimately impair water and nutrient availability, reduce plant growth and productivity, and adversely affect overall soil health (Ghafoor *et al.*, 2001; Mishra *et al.*, 2015; Murtaza *et al.*, 2021).

The most widely used chemical amendment for sodic soil reclamation is gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), a naturally occurring calcium salt that displaces exchangeable Na^+ with calcium ions (Ca^{2+}), thereby restoring soil structure and enhancing water movement (Shainberg *et al.*, 1989; Qadir *et al.*, 2007). Gypsum's effectiveness, however, depends not only on its calcium content but also on its solubility behaviour, defined here as the solubility index, which reflects the rate and amount of calcium it can release into the soil solution over time. Pure agricultural-grade gypsum typically exhibits a solubility of 2.4-2.6 g/L at 25°C (Keren & Shainberg, 1980), but the dissolution rate is strongly affected by

particle size, impurities, temperature, and the presence of other minerals. Over the last decade, alternative gypsum sources have gained interest, including phosphogypsum (PG), a byproduct of phosphoric acid production; marine gypsum, sourced from seawater-evaporation-based table-salt-making process; and industrial by-product gypsum, which is produced from various chemical processes such as flue-gas desulfurization (FGD) (Basak *et al.*, 2022; Evangelou & Karathanasis, 1984). These alternative gypsum sources can differ substantially in purity, solubility, and calcium-release potential (Figure 1). Such variability, together with differences in crystalline structure and contaminant levels (e.g., heavy metals and fluorides), may influence their dissolution kinetics and, ultimately, their effectiveness in sodic soil reclamation (Singh & Rengel, 2007; Asadzadeh *et al.*, 2022).

Given these variations, the need for quantitative comparison of gypsum sources under standard testing conditions is evident. Yet, despite their widespread use in soil science, relatively few studies have systematically compared the dissolution behaviour and calcium release potential of diverse gypsum amendments under time-controlled experimental conditions. Even fewer studies have coupled this with statistical assessments of solubility and calcium availability across material types and simulated application durations. The temporal aspect of solubility is critically important in practical applications. Gypsum materials that dissolve too

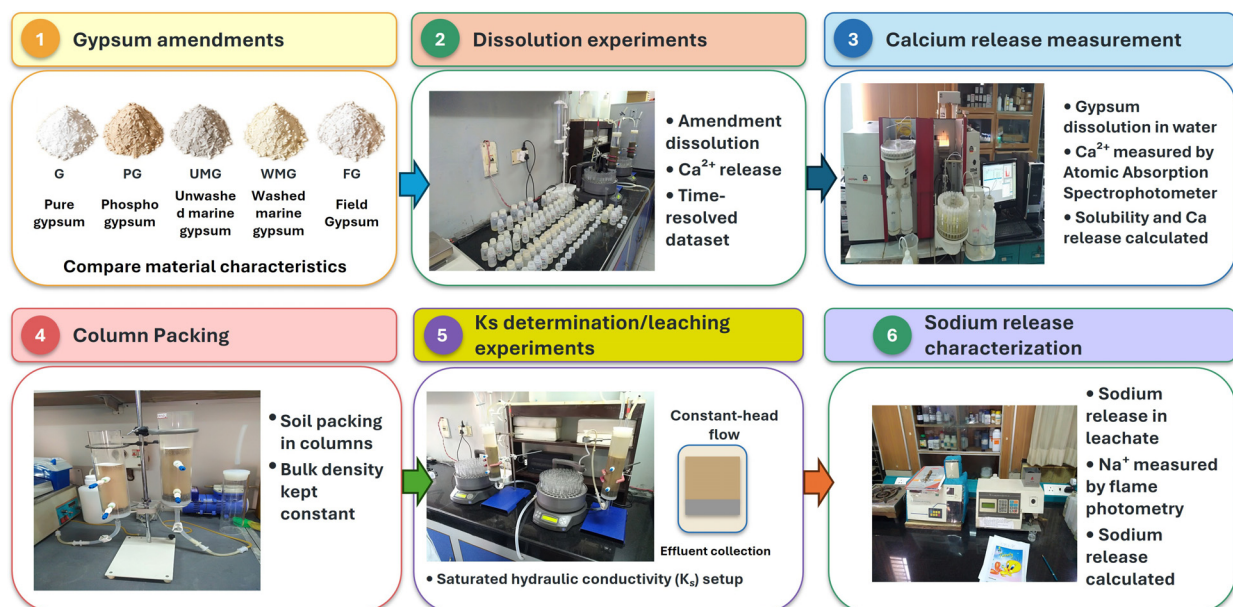


Fig. 1. An illustration of the process followed for comparative evaluation of some gypsum sources for sodic soil reclamation

rapidly may leach out of the root zone before exchanging with sodium ions, especially in coarse-textured or leached soils, leading to inefficient usage. On the other hand, amendments with slow solubility may fail to meet the immediate demands of soil remediation, particularly when used for high-exchangeable sodium percentage (ESP) soils (Asei *et al.*, 2021; Gunal, 2021). Thus, understanding how each amendment behaves over time intervals, e.g., 30, 60, 240 minutes can inform both short-term remediation goals and long-term amendment planning. The solubility of gypsum is also relevant for irrigation water quality improvement, where it is used to treat sodic or alkaline water by providing a readily available source of calcium to reduce sodium adsorption ratio (SAR). In this context, solubility kinetics again play a pivotal role, as amendments must dissolve quickly enough to neutralize sodium during water-soil contact events (Dahlawi *et al.*, 2018; Qadir & Oster, 2004). Moreover, with increasing emphasis on circular economy and industrial waste valorization, using alternative gypsum sources aligns with environmental and economic goals, provided their performance is comparable to natural gypsum.

In this study, we present a comparative solubility and calcium release analysis of five different gypsum-based soil amendments: (1) pure agricultural gypsum (G), (2) phosphogypsum (PG), (3) washed marine gypsum (MG-W), (4) unwashed marine gypsum (MG-WG), and (5) field-collected gypsum. The materials were subjected to standardized laboratory shaking at 30, 60, and 240 minutes to mimic soil solution agitation from rainfall or irrigation. Solubility was assessed gravimetrically, while calcium release was determined via titration. Purity was calculated based on theoretical vs. experimental calcium yield. This study was designed to evaluate and compare the solubility index of both natural and industrial gypsum amendments under laboratory conditions simulating field-like water-soil interactions. It also aimed to quantify the calcium release potential of each material and investigate its relationship with chemical purity. Statistical analyses, including ANOVA and Tukey's HSD test, were employed to identify significant differences among amendment types. Through this work, we propose a performance-based framework to guide the selection of gypsum amendments based on solubility behaviour and calcium bioavailability, with the broader goal of enhancing site-specific soil reclamation practices and promoting sustainable land management in saline and sodic environments.

MATERIALS AND METHODS

Soil collection and characterization

Three sodic soils differing in their physicochemical characteristics were collected from distinct geographical locations in India for use in the laboratory/controlled experiment conducted at the ICAR-Central Soil Salinity Research Institute (CSSRI), Karnal, Haryana. The soils were collected from Sitamai, Karnal, Haryana (Soil A); Khanda, Jind, Haryana (Soil B); and Shivri, Lucknow, Uttar Pradesh (Soil C). The collected soil samples were air-dried, gently crushed, and passed through a 2-mm sieve before use. Initial soil properties, including pH, electrical conductivity (EC), cation exchange capacity (CEC), and exchangeable sodium percentage (ESP), were determined using standard analytical procedures. The three soils exhibited contrasting physicochemical characteristics, with pH ranging from 8.8 to 10.5, EC from 0.82 to 7.47 dS m⁻¹, CEC from 50.9 to 57.5 meq 100 g⁻¹, and ESP from 39.68 to 52.1% (Table 1).

Table 1. Initial physicochemical properties of the three sodic soils collected from different locations

Soil	Location	pH	EC (dS m ⁻¹)	CEC (meq 100 g ⁻¹)	ESP (%)
A	Sitamai	10.3	0.82	57.5	47.4
B	Khanda	10.5	7.47	53.7	39.68
C	Shivri	8.8	2.52	50.9	52.1

Gypsum amendment sources

Five gypsum materials representing different sources were evaluated in the study *viz*; 1) pure gypsum (G), a high-purity gypsum (CaSO₄·2H₂O); 2) phosphogypsum (PG), a by-product generated during phosphoric acid production; 3) washed marine gypsum (MG-W), a marine-derived gypsum obtained through seawater evaporation and subjected to washing prior to use; 4) unwashed marine gypsum (MG-UW), a marine-derived gypsum used without washing; and 5) field gypsum (FG), collected from an open-pit mining source without further treatment. Prior to the experiment, all gypsum materials were air-dried, thoroughly homogenized, and passed through a 2-mm sieve to obtain a uniform particle-size fraction. The prepared samples were subsequently stored in clean, airtight containers until further analysis and experimentation. Each material was air-dried,

homogenized, and sieved to <2 mm to ensure uniform surface area prior to testing.

Experimental Design and Solubility Test

A controlled batch dissolution experiment was conducted to assess the solubility index and calcium release behaviour of each gypsum amendment over time. Each amendment was tested at a constant mass of 5 grams per sample. The samples were placed in 250 mL beakers with deionized water and subjected to mechanical shaking using an orbital shaker at 180 rpm. Three shaking durations were evaluated to simulate varying field water interaction conditions:

1. 30 minutes (short-term leaching)
2. 60 minutes (moderate interaction)
3. 240 minutes (extended irrigation simulation)

After each duration, the suspension was filtered, and the remaining undissolved solid was dried and weighed. The dissolved fraction (g/L) was calculated by subtracting the dry solid from the original 5 g mass and dividing by the volume.

Calcium Quantification

Calcium concentration in water samples was determined using Atomic Absorption Spectrophotometer (AAS). Water samples were filtered through Whatman No. 42 filter paper and acidified with concentrated HNO_3 to pH <2. A series of Ca standard solutions (e.g., 0, 1, 2, 5, 10 and 20 mg L^{-1}) was prepared from a certified calcium stock standard. The instrument was calibrated using the Ca standards, and absorbance of the samples was measured under identical operating conditions. A reagent blank was used for baseline correction. Calcium concentration in the samples was calculated from the calibration curve and expressed as mg Ca L^{-1} . Samples exceeding the calibration range were appropriately diluted with deionized water before analysis. The dataset was drawn from three test replicates ("First Run," "Second Run," and "Third Run"), each consisting of 12 samples per amendment type, totaling 144 observations.

Purity Determination

The purity (%) of each gypsum sample was calculated by comparing the experimentally derived Ca^{2+} concentration to the theoretical maximum obtainable from pure $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$:

$$\text{Purity (\%)} = \left(\frac{\text{Measured } \text{Ca}^{2+} \text{ (meq/L)}}{\text{Theoretical } \text{Ca}^{2+} \text{ for 5g gypsum}} \right) \times 100$$

Theoretical calcium concentration was estimated based on gypsum's molecular weight (172.17 g/mol) and calcium's molar proportion (40.08 g/mol), yielding approximately 2.62 g/L dissolution under ideal conditions.

Hydraulic conductivity

As an indicator of soil structure, changes in saturated HC were measured using disturbed samples and deionized water. Soil columns were prepared by uniformly packing 120 g of air-dried, crushed, and sieved soil (<2.0 mm) into Perspex cylinders (5.4 cm internal diameter and 10.4 cm length) to a dry bulk density of $1.165 \pm 0.015 \text{ Mg m}^{-3}$. The bottom of each cylinder contained a 5.0 cm layer of acid-washed sand over a fine metal sieve to facilitate drainage. A filter paper covered the soil surface to minimize disturbance during wetting and leaching.

The soil columns were wetted from below with deionized water ($\text{EC } 0.004 \text{ dS m}^{-1}$). The degree of slaking of the aggregates was manipulated by wetting the soil in the columns at a rate of 2 mm h^{-1} (almost no slaking, designated as slow wetting) or 50 mm h^{-1} (severe slaking, designated as fast wetting) using a peristaltic pump. When the water level reached the top of the soil columns, the flow direction was reversed, and the columns were leached from the top with deionized water from a Mariotte bottle with a constant head of 10 cm. The leachate was collected continuously over fixed time intervals using a fraction collector, and the HC was then calculated. The Na^+ concentration was determined using a flame photometer.

Statistical Analysis

To determine whether solubility and calcium release differed significantly among gypsum types and time durations, the data were analyzed using one-way and two-way Analysis of Variance (ANOVA), followed by post-hoc pairwise comparisons using Tukey's Honest Significant Difference (HSD) test at a 95% confidence level ($\alpha = 0.05$). The assumptions of normality and homogeneity of variances were verified prior to conducting ANOVA. Statistical analyses were performed using Python 3.10. Graphical analyses included boxplots and bar charts with error bars

(mean $\pm$ SD), correlation plots showing the relationship between solubility and Ca^{2+} release, and time-based solubility trend plots for each amendment. All data and analysis scripts were archived and made available upon request to facilitate reproducibility.

RESULTS

Hydraulic conductivity

Hydraulic conductivity varied among gypsum amendments, soils, and measurement time (Figure 2). In Sitamai soil, pure gypsum (G) showed a marked increase in hydraulic conductivity during the initial period, rising from 0.027 cm h^{-1} at 2 h to 0.055 cm h^{-1} at 6-8 h, followed by a gradual decline and stabilization at approximately 0.041 cm h^{-1} towards the end of the experiment. Phosphogypsum (PG) increased from 0.017 cm h^{-1} at 2 h to approximately 0.031 cm h^{-1} at 22 h, followed by a gradual increase to 0.034 cm h^{-1} at 44 h. Washed marine gypsum (MG-W) maintained relatively high

hydraulic conductivity throughout the experiment, increasing from 0.036 cm h^{-1} at 2 h to 0.046 cm h^{-1} at 40-44 h. In contrast, unwashed marine gypsum (MG-UW) recorded the lowest initial hydraulic conductivity (0.014 cm h^{-1} at 2 h) but increased progressively to 0.037 cm h^{-1} at 38-44 h. Overall, G showed the highest hydraulic conductivity during the initial period, whereas MG-W maintained the highest values towards the later stages of the experiment. At 44 h, hydraulic conductivity followed the order MG-W (0.046) > G (0.041) > MG-UW (0.037) > PG (0.034 cm h^{-1}).

In Khanda soil, hydraulic conductivity showed a contrasting temporal response among the gypsum amendments. Pure gypsum (G) remained relatively low during the initial period, increasing from 0.018 cm h^{-1} at 6 h to 0.030 cm h^{-1} at 20 h, followed by fluctuations and a subsequent increase to 0.027 cm h^{-1} at 38-44 h. Phosphogypsum (PG) remained comparatively low throughout the experiment, ranging from approximately 0.013 to 0.021 cm h^{-1} , with a value of 0.019 cm h^{-1} at 44 h.

Washed marine gypsum (MG-W) recorded relatively high hydraulic conductivity initially, reaching 0.044 cm h^{-1} at 6 h, but declined progressively to 0.013 cm h^{-1} at 44 h. Unwashed marine gypsum (MG-UW) exhibited the highest initial hydraulic conductivity, reaching 0.054 cm h^{-1} at 4-6 h, followed by a progressive decline to 0.017 cm h^{-1} at 44 h. Thus, MG-UW and MG-W showed the highest hydraulic conductivity during the early period, whereas G recorded the highest value at the end of the experiment.

In Shivri soil, hydraulic conductivity varied among gypsum amendments and over time (Figure 2). Pure gypsum (G) showed a marked increase in hydraulic conductivity during the initial period, rising from approximately 0.027 cm h^{-1} at 2 h to 0.055 cm h^{-1} at 6-8 h, followed by a gradual decline and stabilization at around 0.041 cm h^{-1} towards the end of the experiment. Phosphogypsum (PG) increased gradually from approximately 0.017 cm h^{-1} at 2 h to 0.034 cm h^{-1} at 42-44 h. Washed marine gypsum (MG-W) maintained relatively high hydraulic conductivity throughout the experiment, increasing from 0.036 cm h^{-1} at 2 h to a maximum of 0.048 cm h^{-1} at 32-34 h, followed by a slight decline to 0.046 cm h^{-1} at 40-44 h. In contrast, unwashed marine gypsum (MG-UW) showed the lowest initial hydraulic conductivity (0.014 cm h^{-1}) but increased progressively to 0.037 cm h^{-1} at 38-44 h. Overall, G

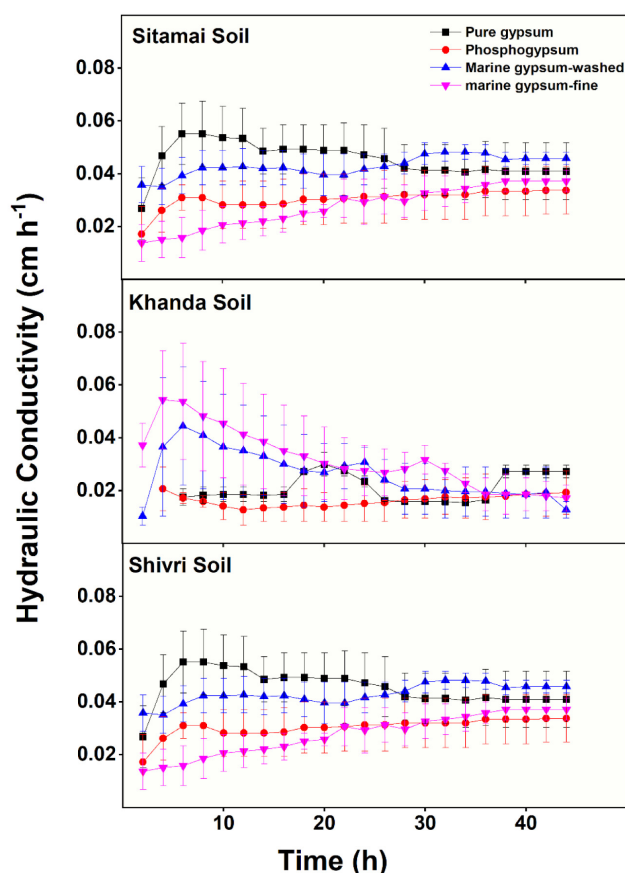


Fig. 2. Temporal changes in hydraulic conductivity of sodic soils amended with different gypsum sources

showed the highest hydraulic conductivity during the initial period, whereas MG-W maintained the highest values during the later stages of the experiment. At 44 h, hydraulic conductivity followed the order MG-W (0.046) > G (0.041) > MG-UW (0.037) > PG (0.034 cm h⁻¹).

Na⁺ concentration

In Sitamai soil, Na⁺ concentration differed considerably among the four gypsum amendments over time (Figure 3). Phosphogypsum (PG) generally recorded the highest Na⁺ concentration, increasing from 9,660 ppm at 8 h to a maximum of 16,130 ppm at 26 h, followed by a gradual decline to 10,930 ppm at 44 h. Pure gypsum (G) showed a progressive increase during the initial period, from 1,001 ppm at 4 h to 9,460 ppm at 18 h, followed by fluctuations and reaching 12,050 ppm at 44 h. Washed marine gypsum (MG-W) maintained considerably lower Na⁺ concentrations, ranging from 2,725 to 4,620 ppm, while unwashed marine gypsum (MG-UW) recorded the lowest concentrations, increasing gradually from 240 ppm at 14 h to 2,590 ppm at 42

h, followed by a slight decline to 2,280 ppm at 44 h. Thus, the overall concentration pattern in Sitamai soil was phosphogypsum (PG) > pure gypsum (G) > washed marine gypsum (MG-W) > unwashed marine gypsum (MG-UW) for most of the experimental period.

In Khanda soil, phosphogypsum (PG) initially recorded the highest Na⁺ concentration, reaching approximately 13,490 ppm at 4 h, followed by a gradual decline to 6,200 ppm at 44 h. Pure gypsum (G) showed relatively high Na⁺ concentrations, increasing from 7,170 ppm at 6 h to 12,310 ppm at 22 h, followed by fluctuations and a decline to 7,960 ppm at 44 h. Washed marine gypsum (MG-W) showed a gradual increase throughout the experiment, from approximately 988 ppm at 2 h to 4,640 ppm at 42 h, with a slight decline thereafter. Unwashed marine gypsum (MG-UW) maintained the lowest Na⁺ concentration during most of the experiment, increasing from approximately 120 ppm at 2 h to 3,770 ppm at 44 h. Overall, Na⁺ concentration was generally highest under phosphogypsum (PG), followed by pure gypsum (G), whereas washed marine gypsum (MG-W) and unwashed marine gypsum (MG-UW) maintained substantially lower concentrations.

In Shivri soil, phosphogypsum (PG) exhibited substantially higher Na⁺ concentrations than the other amendments, reaching approximately 17,000–18,500 ppm during the early period, followed by a decline and subsequent fluctuations, with concentrations remaining around 8,000–11,000 ppm during the later stages. Pure gypsum (G) maintained considerably lower Na⁺ concentrations than phosphogypsum (PG) but generally remained higher than the marine gypsum amendments.

Washed marine gypsum (MG-W) showed relatively stable Na⁺ concentrations of approximately 3,000–4,000 ppm throughout the experiment. Unwashed marine gypsum (MG-UW) generally recorded the lowest Na⁺ concentrations, remaining mostly around 1,500–3,000 ppm. Overall, the four amendments showed a clear separation in Na⁺ concentration, with phosphogypsum (PG) recording the highest values, followed by pure gypsum (G), washed marine gypsum (MG-W), and unwashed marine gypsum (MG-UW).

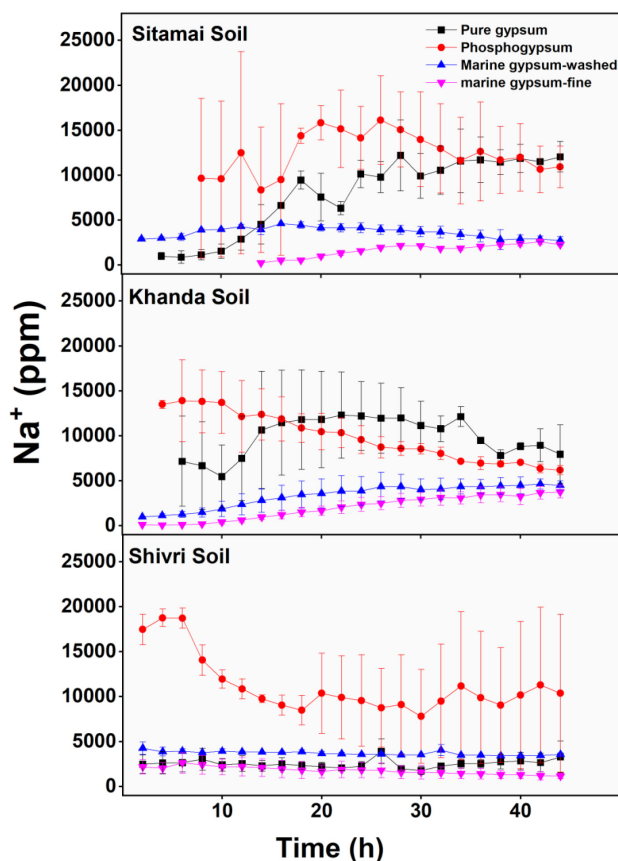


Fig. 3. Temporal variation in Na⁺ concentration of different sodic soils amended with different gypsum sources

Solubility Behaviour of Gypsum Amendments

The quantity of gypsum dissolved varied among the five gypsum amendments, ranging from 1.55 to

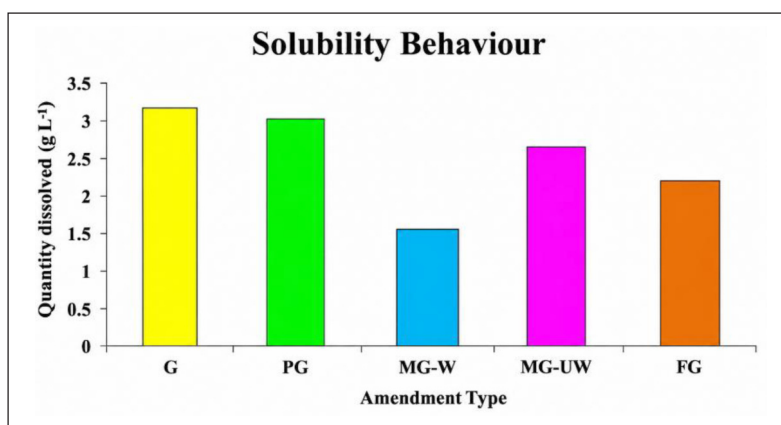


Fig. 4. Comparative solubility behaviour of gypsum amendments

3.14 g L⁻¹ under the experimental dissolution conditions (Figure 4). Pure gypsum (G) recorded the highest quantity dissolved (3.1474 g L⁻¹), followed by phosphogypsum (PG) with 3.0161 g L⁻¹. Unwashed marine gypsum (MG-UW) showed an intermediate quantity dissolved (2.6549 g L⁻¹), while field gypsum (FG) recorded 2.1926 g L⁻¹. Washed marine gypsum (MG-W) exhibited the lowest quantity dissolved (1.5552 g L⁻¹). Overall, the quantity dissolved followed the order G > PG > MG-UW > FG > MG-W, indicating differences in dissolution behaviour among the gypsum sources and processing conditions.

The relatively greater quantity dissolved from G and PG indicates higher dissolution under the experimental conditions, whereas MG-W showed substantially lower dissolution. The intermediate values observed for MG-UW and FG indicate moderate dissolution compared with the other amendments. These differences in the quantity of gypsum dissolved may influence the availability of Ca²⁺ in the soil solution and, consequently, the effectiveness of different gypsum sources for sodic soil reclamation.

Calcium Availability and Amendment Purity

Calcium release and purity varied considerably among the gypsum amendment types (Figure 5). Pure gypsum (G) recorded the highest Ca²⁺ concentration of 32.6 meq L⁻¹, closely followed by unwashed marine gypsum (MG-UW) with 32.4 meq L⁻¹. Phosphogypsum (PG) showed a slightly lower Ca²⁺ concentration of 30.7 meq L⁻¹, whereas washed marine gypsum (MG-W) and field gypsum (FG) recorded comparatively lower values of 23.2 and 20.4 meq L⁻¹, respectively.

A similar variation was observed in the purity of the amendments. G showed the highest purity (81.5%), closely followed by MG-UW (81.0%), while PG recorded 76.8% purity. In contrast, MG-W and FG had considerably lower purity values of 58.0 and 51.0%, respectively. Overall, the amendments with higher purity, particularly G and MG-UW, also showed greater Ca²⁺ release, whereas the lower-purity materials, MG-W and FG, exhibited comparatively lower Ca²⁺ concentrations. These results demonstrate clear differences among gypsum sources in their chemical quality and calcium-supplying capacity under the experimental conditions.

Correlation Between Solubility, Calcium Release, and Purity

A multivariate correlation analysis was performed to examine the relationships among solubility (g L⁻¹), calcium release (meq L⁻¹), and chemical purity (%) of the five gypsum amendments (Figure 6). The analysis showed positive relationships among all three parameters. Solubility was positively associated with calcium release, indicating that gypsum amendments with greater dissolution generally released higher amounts of Ca²⁺ into the solution. This relationship was evident for G, PG, and MG-UW, which showed relatively high solubility and calcium release, whereas MG-W and FG exhibited lower values for both parameters. Solubility also showed a positive association with purity, although the relationship was less consistent than that between calcium release and purity. The strongest relationship was observed between calcium release and purity, with higher-purity gypsum materials generally releasing greater amounts of

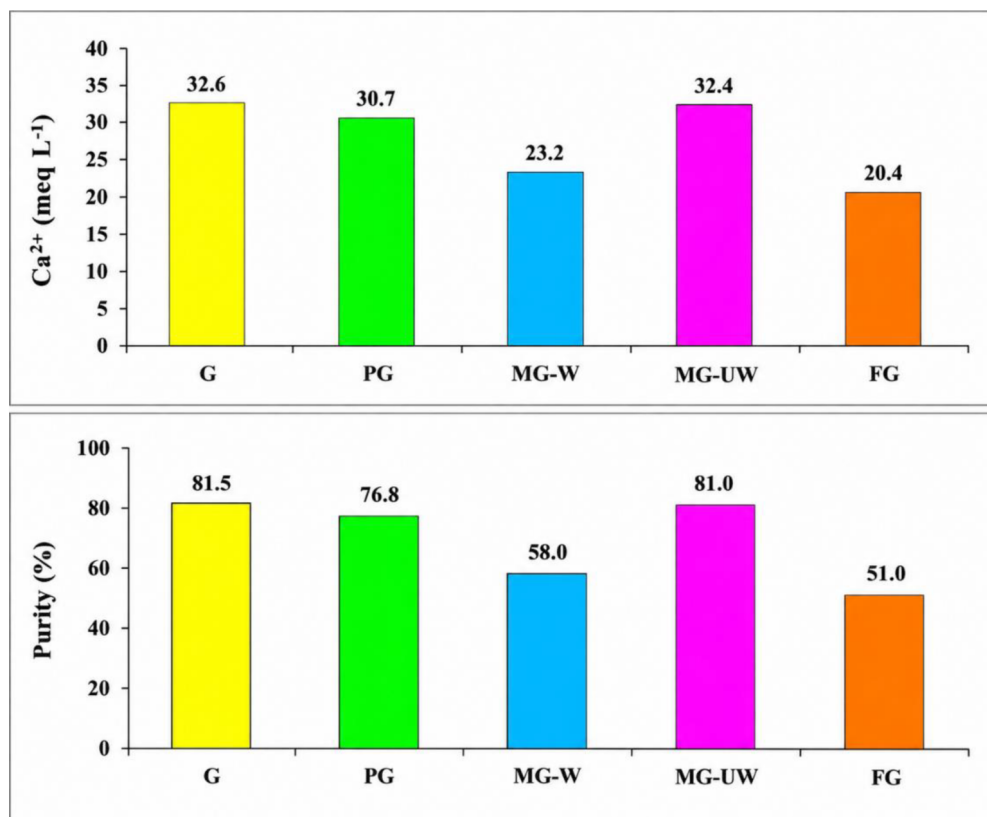


Figure 5. Calcium concentration and purity of different gypsum amendments

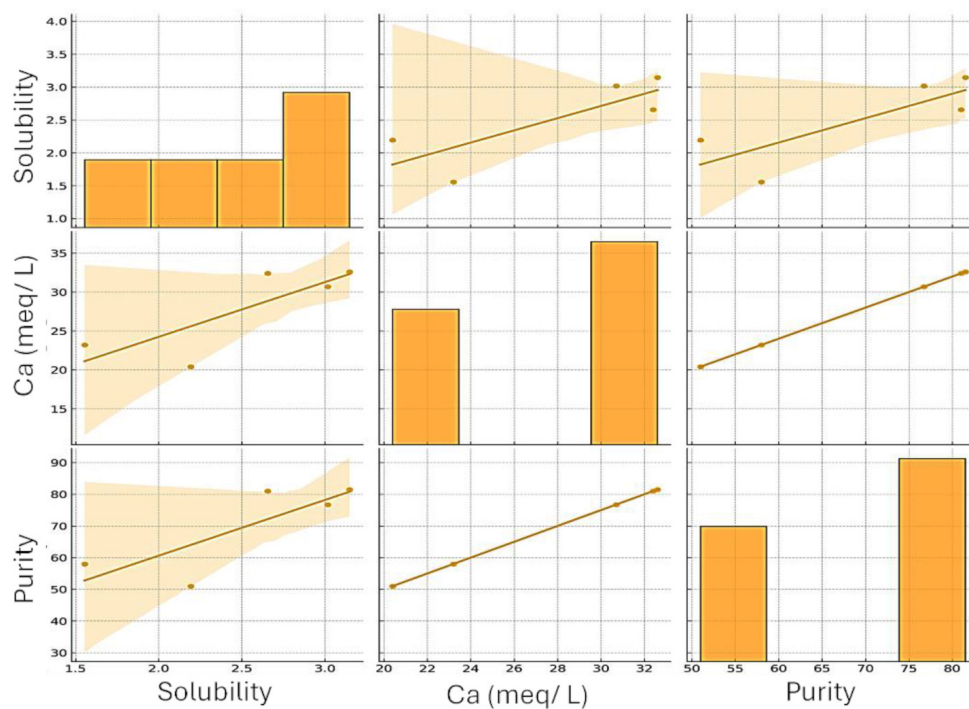


Figure 6. Correlation among solubility, calcium release, and purity of different gypsum amendments

Ca²⁺. G and MG-UW showed both high purity and high calcium release, whereas FG and MG-W had comparatively lower purity and calcium release. Overall, the correlation analysis indicates that gypsum purity was closely associated with calcium release, while solubility was also positively related to both parameters. These relationships suggest that purity, dissolution behaviour, and calcium release are closely interconnected characteristics of the tested gypsum amendments.

DISCUSSION

The dissolution behaviour and calcium release characteristics of gypsum-based soil amendments are critical determinants of their agronomic effectiveness, particularly in the reclamation of sodic. This study demonstrated that solubility, calcium availability, and chemical purity varied among amendment types, and these variations interact to shape their potential suitability for soil remediation.

Among the tested materials, pure gypsum (G) exhibited the highest quantity dissolved (3.1474 g L⁻¹), followed by phosphogypsum (PG; 3.0161 g L⁻¹) and unwashed marine gypsum (MG-UW; 2.6549 g L⁻¹) under controlled conditions. Field gypsum (FG) showed an intermediate quantity dissolved (2.1926 g L⁻¹), whereas washed marine gypsum (MG-W) exhibited the lowest value (1.5552 g L⁻¹). This finding aligns with previous literature emphasizing the importance of material origin and pre-treatment in determining dissolution behaviour (Bello *et al.*, 2021). The relatively high dissolution of MG-UW may be associated with differences in particle surface characteristics and the presence of soluble surface constituents, which may enhance water–solid interaction. Pure gypsum, as expected, also showed high dissolution, which may be related to its high mineralogical uniformity and low impurity content.

Phosphogypsum (PG) presented relatively high dissolution (3.02 g L⁻¹) and calcium concentration (30.7 meq L⁻¹), supporting its potential use as an affordable amendment when managed for potential trace contaminant risks (Sundha *et al.*, 2023). Washed marine gypsum (MG-W), however, showed markedly lower dissolution (1.56 g L⁻¹) and calcium availability (23.2 meq L⁻¹). These findings suggest that washing, while helpful for removing salts, may alter the surface characteristics or remove readily soluble phases, thereby lowering its dissolution potential (Sundha *et al.*, 2023). Field gypsum (FG)

showed lower calcium release (20.4 meq L⁻¹) and relatively low dissolution (2.19 g L⁻¹), while its purity (51.0%) was the lowest among all samples. The lower calcium release may be associated with the presence of non-gypsum mineral constituents and differences in the characteristics of the field-collected material. Similar challenges with field-collected gypsum were noted by Delavar *et al.* (2021), who emphasized the importance of pre-screening natural sources for agronomic applications.

A positive relationship was observed between calcium release and both solubility and purity. Amendments with higher purity generally released more calcium into solution, indicating that chemical composition contributes substantially to amendment performance (Gashi *et al.*, 2025). Interestingly, although purity and solubility were positively correlated, the association was less consistent than the relationship between calcium release and purity. This indicates that other factors such as porosity, particle size distribution, surface characteristics, and crystal defects may also modulate dissolution independent of purity. The statistical analysis supports this, as both one-way and two-way ANOVA revealed significant differences ($p < 0.05$) in solubility and calcium release across amendment types, but not across shaking durations. This suggests that intrinsic material properties may have a greater influence on the measured performance than exposure time under the experimental conditions, particularly under near-saturation conditions. The interaction between amendment type and shaking duration was minimal in statistical terms, with relative differences among the amendments remaining generally consistent across the evaluated shaking durations. However, differences in absolute dissolution with increasing duration were observed among the materials, consistent with classical dissolution kinetics, where surface reactions proceed rapidly initially and subsequently approach equilibrium or saturation conditions.

These findings corroborate the work of Kumar *et al.* (2022), who reported that most gypsum dissolution occurs within the first hour of application, after which further dissolution contributes marginally to calcium availability. The observed differences among G, PG, MG-UW, FG, and MG-W indicate that the intrinsic properties of the amendment material can influence the amount of gypsum dissolved and calcium released under controlled conditions. These results reinforce the

concept that the selection of gypsum amendments must be based on more than cost or availability. As evidenced in this study, G and MG-UW showed high calcium release, while G also exhibited the highest quantity dissolved. PG also showed relatively high dissolution and calcium release. In contrast, MG-W showed the lowest dissolution, while FG recorded the lowest calcium release and purity. These differences indicate that amendment characteristics should be considered when selecting gypsum materials for soil reclamation, particularly where rapid calcium availability is required.

From a sustainability and policy perspective, incorporating quality metrics such as solubility index and chemical purity into procurement criteria could enhance the effectiveness of large-scale remediation programs. Moreover, blended strategies combining high-solubility materials with bulk fillers or organic amendments may balance cost, reactivity, and environmental impact (Zhang *et al.*, 2024). These findings provide a nuanced framework for amendment selection and suggest that the appropriate gypsum product should be chosen based on its intrinsic chemical profile, dissolution behaviour, calcium-release capacity, and the desired remediation timeline.

CONCLUSION

The present study demonstrates that the effectiveness of gypsum amendments for the reclamation of sodic soils is governed by the combined effects of amendment source, chemical purity, dissolution characteristics, and calcium-release capacity. The evaluated gypsum materials differed considerably in their dissolution behaviour and ability to release calcium, reflecting differences in composition and processing history. The positive association between gypsum purity, dissolution, and calcium availability highlights the importance of assessing amendment quality before application. However, calcium release did not always correspond directly with the amount of material dissolved, indicating that both dissolution behaviour and the calcium content of the amendment influence its reclamation potential. The effects of gypsum amendments on hydraulic conductivity and sodium concentration varied with soil type and initial soil characteristics. These findings emphasize that amendment performance cannot be evaluated independently of the properties of the target soil. Gypsum materials with higher dissolution and

calcium-release capacity may enhance calcium availability, sodium displacement, soil structure, and water movement during reclamation. Phosphogypsum may also serve as a useful alternative gypsum source when its chemical composition safety is adequately assessed.

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