



RESEARCH ARTICLE

Yellow gypsum amendment enhances nutrient availability and mitigates arsenic bioavailability in arsenic-contaminated soils under a kharif groundnut-boro rice cropping system

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Abstract

Yellow gypsum (YG), a synthetic gypsum derived from LD slag (steel industry by-product), is alkaline in nature and contains appreciable amounts of essential plant nutrients. Due to its chemical composition, YG has potential as a soil amendment to improve nutrient availability and reduce arsenic (As) mobility in contaminated soils. The present study evaluated the effectiveness of YG as a source of calcium (Ca), sulfur (S), silicon (Si) and iron (Fe) in kharif groundnut and boro-rice cropping systems grown in As-contaminated soil. A series of pot experiments was conducted during 2019–2021 using a factorial completely randomized design (FCRD) with 17 levels of As treatments and three levels of YG application (0, 30 and 60 kg ha⁻¹). Irrespective of As treatments, the application of YG significantly ($p < 0.05$) increased the availability of S, Si and phosphorus (P), as well as exchangeable Ca and Diethylenetriaminepentaacetic acid (DTPA)-extractable Fe, across different growth stages of both crops. The YG application also resulted in a slight increase in soil pH. A significant ($p < 0.05$) increase in soil organic carbon (OC) was observed with YG application, whereas lower values were recorded in the control treatment (Y₀). Increasing As levels in soil were inversely related to the availability of Ca, S, Si and P, while no significant effect ($p > 0.05$) was observed on soil Fe and manganese (Mn) contents. Among the treatments, the application of gypsum (YG) at 60 kg ha⁻¹ proved to be the most effective rate for improving soil nutrient availability in both crops under As-contaminated conditions. The results suggest that YG can serve as a beneficial soil amendment for enhancing soil fertility and managing nutrient dynamics and reducing the bioavailability of As in As-contaminated soils.

Keywords: arsenic; amendment; factorial complete randomized design; nutrient availability; pot experiment; slag gypsum; soil remediation; yellow gypsum

Introduction

Gypsum is a widely utilized mineral with diverse applications in the cement industry, plaster manufacturing and agricultural soil management. In agriculture, gypsum is commonly applied as a soil amendment to improve soil physical properties, enhance soil aggregation and regulate nutrient dynamics by supplying essential nutrients such as calcium (Ca) and sulfur (S). The application of gypsum helps improve soil structure, reduce soil compaction and enhance water infiltration and root growth. Natural Gypsum, which is known as hydrated calcium sulfate (CaSO₄ · 2H₂O), is commonly used as an amendment for alkaline soils and as a source of Ca and S for oilseed crops (1, 2). Natural mineral resources are the major raw materials for fertiliser production and are being exhausted due to increased stress from the growing population and food demand. Therefore, in the current scenario, various value-added industrial waste-based

nutrient supplements would help reduce the depletion rate of natural mineral resources.

In the past, most of the industrially produced gypsum was used in the medical field, as a retarder in the cement industry, as a starting material for the production of other building elements and a very small amount was used for agricultural purposes (3). Like other countries, India has only a few mineable reserves of elemental S and imports most S-related minerals (4). Therefore, gypsum produced from steel industry wastes such as Linz-Donawitz slag (LD slag), which is rich in Ca-bearing silicates and some metallic Fe, can be effectively used in the conservation of natural gypsum (5). LD slag contains an appreciable amount of calcium oxide (CaO) (49.16 %), silica (SiO₂) (11.75 %), ferrous oxide (FeO) (11.61 %), magnesium oxide (MgO) (4.21 %) and phosphorus (P) in the form of phosphorus pentoxide (P₂O₅) (2.32 %) and a small amount of

aluminum (Al), manganese (Mn) and chromium (Cr) (6, 7). These industrial slags can be used in cement manufacturing, concrete and road aggregates, fertiliser and metal stabilisation in contaminated soils (8, 9). The scientific community throughout the world has made a priority of finding ways to increase the value of industrial by-products and to reduce their wastes. The Yellow Gypsum (YG) (Slag-Based Gypsum) is prepared by acid treatment of 60-mesh LD slag fines with concentrated sulphuric acid, followed by neutralisation with a 20 % lime solution. During this process, all heavy metals and impurities will be leached into the solution, while Ca and Si remain insoluble (6). This YG is commonly called “YG” owing to its yellow color due to the presence of iron (Fe) in the slag. Slag Based Gypsum (YG) contains quite good amount of Ca (23.03 %), S (17.38 %), Fe (5.92 %) and silicon (Si) (3.47 %) and small amounts of P, magnesium (Mg), Mn and aluminum (Al) and hazardous metals like Cr (117.20 $\mu\text{g g}^{-1}$), nickel (Ni) (2.85 $\mu\text{g g}^{-1}$), copper (Cu) (4.41 $\mu\text{g g}^{-1}$) and cadmium (Cd) (1.29 $\mu\text{g g}^{-1}$) are quite below the limits of Toxicity Characteristic Leaching Procedure (TCLP) (7, 10). Hence, there is a need to study the potential of Gypsum (YG) and its suitability for agricultural use. The present work explored the potential of YG as a soil amendment in arsenic (As)-contaminated soil and its influence on other soil parameters grown under kharif groundnut and boro rice.

Material and Methods

Experiment design and treatment details

In West Bengal, the Panchpota area of Nadia district is recognized as a severely As-affected region due to the prolonged use of As-contaminated groundwater for irrigation. Therefore, surface bulk soil samples were collected from rice-growing fields at a depth of 0–0.15 m, representing the plow layer where most root activity, nutrient cycling and contaminant accumulation occur. Sampling at this depth is widely used in soil science studies to assess nutrient status and contaminant dynamics in agricultural soils (11). Moreover, the 0–15 cm layer is generally considered the representative topsoil horizon for evaluating soil fertility and contaminant behavior in cultivated soils, as it is the zone most directly influenced by agricultural management practices and crop growth (12). To set up the pot experiment, the soil was thoroughly processed by removing roots and debris and each earthen pot was filled with 5 kg of processed soil. Seventeen different concentrations of As treatments (0 to 24 ppm of As with a difference of 1.5 ppm between each treatment) were made by spiking the soil with As. This was done by using sodium arsenite (NaAsO_2) in different pots and allowed to equilibrate for one month. After equilibration, soil was collected from the pots and initial characteristics were analyzed (Table 1). In our experiment, the first crop, Groundnut (TG-51), was grown in the kharif season, followed by Rice (Shatabdi: IET-4786) during the boro season in these pots. The experiment was laid out with seventeen concentrations of As and three levels of YG (Y_0 : 0 kg ha^{-1} , Y_{30} : 30 kg ha^{-1} and Y_{60} : 60 kg ha^{-1}) as an amendment in a completely randomized block design with three replications. Arsenic was spiked in the pots only once during the entire experiment. The entire experiment was carried out in open-chamber conditions. Each treatment received three doses of YG in a completely randomized block design. Three levels of YG were applied to the pots two weeks before sowing or transplanting the crop and the pots were left to equilibrate.

Amendment and fertiliser application

Three YG levels (0, 30 and 60 kg ha^{-1}) were applied in pots as a basal application to each crop two weeks before sowing or transplanting and the pots were left to equilibrate. All treatments received a uniform amount of N, P and K as urea, Single Superphosphate (SSP) and Muriate of Potash (MOP). Nitrogen was applied twice as split doses as a basal dose and during the flowering stage of groundnut and the maximum tillering stage of rice. Full dose of P and K and half dose of N were applied 7 days before sowing or transplanting of the crop. Both crops received recommended doses of fertilizer at the rate of 25:50:50 kg NPK ha^{-1} for kharif groundnut and 120:60:60 kg NPK ha^{-1} for boro-rice.

Soil sampling

During the kharif season, Groundnut (cv. TG-51) was sown using three seeds per pot. Similarly, 30-day-old rice seedlings (cv. Shatabdi, IET 4786) were transplanted during the boro season, with three rice hills (two seedlings per hill) per pot. Soil was collected at 45 days after sowing and transplanting and at harvest of each season by destructive sampling method, for recording observation in groundnut and rice crop, respectively. The data presented in this paper are pooled over two seasons in each crop.

Determination of soil parameters

Soil pH

Accurately weighed 10 g soil along with 25 mL of distilled water was taken in a 50 mL glass beaker and the mixture was stirred with the help of glass rod and after equilibration pH was measured by dipping a glass electrode and a reference Calomel electrode in the bulk solution with the help of a pH meter in 1:2.5 soil : water suspension ratio as described by Jackson (13).

Oxidizable organic carbon estimation

Accurately weighed 0.5 g of soil sample was taken in a 500 mL conical flask followed by addition of 10 mL of 1N potassium dichromate ($\text{K}_2\text{Cr}_2\text{O}_7$) solution and 20 mL of concentrated sulphuric acid (H_2SO_4) (36N) and the conical flask was kept in dark for 30 minutes. The conical flask was then taken out and 200 mL of distilled water was added to it immediately. About 5 mL of orthophosphoric acid (H_3PO_4) (88%) and 2–3 drops of diphenylamine indicator were added to it followed by titration against 0.5 N ferrous ammonium sulfate [$(\text{NH}_4)_2\text{Fe}(\text{SO}_4)_2 \cdot 6\text{H}_2\text{O}$] till end point (dark violet to dirty green colour) was reached (14).

Organic carbon (%) = $[(V_b - V_s) \times N \times 0.003 \times 1.33 \times 100] / W$ (Eqn. 1)

Where:

V_b = Volume of ferrous ammonium sulfate used for blank (mL)

V_s = Volume used for sample (mL)

N = Normality of ferrous ammonium sulfate

W = Weight of soil sample (g)

1.33 = Correction factor

Estimation of available phosphorus

Accurately weighed 2.5 g of soil was shaken for 30 min with 50 mL 0.5M NaHCO_3 (pH-8.5) to which 1 spoonful of activated charcoal was added and filtered using Whatman no. 42 filter paper in a polythene bottle. A 10 mL portion of the filtrate was pipetted out in a 50 mL volumetric flask and the pH was adjusted to 5.0 using 2.5 (M) sulphuric acid. Then 8 mL of mixed reagent [(50 mL of 2.5 (M) sulphuric acid, 15 mL of ammonium molybdate, 30 mL ascorbic acid and 5 mL antimony potassium tartarate] was added and the

Table 1. Initial chemical properties of the experimental soil

Treatment		pH	OC (g kg ⁻¹)	P (mg kg ⁻¹)	S (mg kg ⁻¹)	Si (mg kg ⁻¹)	Ca (cmol(P+) kg ⁻¹)	Mg (cmol(P+) kg ⁻¹)	Fe (mg kg ⁻¹)	Mn (mg kg ⁻¹)
T ₀	n=9	7.23 ^e	6.13 ^{cd}	14.24 ^a	46.01 ^g	31.63 ^b	2.58 ^a	2.28 ^b	51.17	23.08
T ₁	n=9	7.27 ^f	6.17 ^{bc}	13.96 ^b	45.98 ^h	30.90 ^c	2.54 ^{ef}	2.21 ^{ef}	51.17	23.08
T ₂	n=9	7.23 ^g	6.20 ^{ab}	13.96 ^b	46.03 ^{fg}	31.99 ^a	2.56 ^b	2.26 ^c	51.11	23.05
T ₃	n=9	7.24 ^g	6.00 ^{gh}	14.24 ^a	46.02 ^{fg}	30.41 ^e	2.53 ^{fg}	2.23 ^d	50.99	23.00
T ₄	n=9	7.31 ^d	6.07 ^{ef}	13.80 ^{bcd}	45.99 ^h	30.66 ^d	2.55 ^{bc}	2.18 ^g	51.06	23.03
T ₅	n=9	7.33 ^b	6.03 ^{fg}	14.18 ^a	46.10 ^{ab}	31.51 ^b	2.55 ^{cd}	2.31 ^a	50.95	22.98
T ₆	n=9	7.34 ^b	5.90 ^j	13.74 ^{cde}	46.04 ^{ef}	30.41 ^e	2.53 ^g	2.21 ^{ef}	51.00	23.00
T ₇	n=9	7.35 ^a	5.97 ^h	13.69 ^{de}	46.07 ^d	30.53 ^{de}	2.53 ^g	2.19 ^g	50.94	22.97
T ₈	n=9	7.31 ^d	6.10 ^{de}	13.91 ^{bc}	45.97 ^h	30.54 ^{de}	2.54 ^{de}	2.27 ^b	50.93	22.97
T ₉	n=9	7.32 ^{bcd}	6.20 ^{ab}	13.36 ^f	46.10 ^{ab}	29.93 ^f	2.51 ^h	2.22 ^{ef}	51.11	23.05
T ₁₀	n=9	7.32 ^{bcd}	6.23 ^a	13.20 ^{fg}	46.11 ^a	29.32 ^g	2.51 ^h	2.21 ^f	51.18	23.08
T ₁₁	n=9	7.29 ^e	6.20 ^{ab}	13.58 ^e	46.07 ^{cd}	28.83 ^h	2.51 ^h	2.21 ^{ef}	51.14	23.06
T ₁₂	n=9	7.31 ^d	5.90 ^j	13.04 ^{gh}	46.04 ^{ef}	28.83 ^h	2.52 ^h	2.22 ^e	51.29	23.13
T ₁₃	n=9	7.33 ^b	6.07 ^{ef}	12.87 ^h	46.06 ^{de}	28.59 ⁱ	2.48 ⁱ	2.19 ^g	51.18	23.08
T ₁₄	n=9	7.32 ^{cd}	6.10 ^{de}	12.27 ⁱ	46.10 ^{abc}	28.59 ⁱ	2.48 ⁱ	2.26 ^c	51.20	23.09
T ₁₅	n=9	7.34 ^b	5.97 ^h	11.94 ^j	46.08 ^{bcd}	28.83 ^h	2.48 ⁱ	2.23 ^d	51.18	23.08
T ₁₆	n=9	7.33 ^{bc}	5.97 ^h	11.78 ^j	46.07 ^{cd}	28.10 ^j	2.45 ^j	2.24 ^d	51.32	23.14
Range		0.12	0.33	2.46	0.14	3.89	0.13	0.13	0.38	0.17
SEm ±		0.003	0.003	0.005	0.016	0.01	0.002	0.002	0.12	0.054
LSD (<i>P</i> <0.05)		0.007	0.009	0.013	0.044	0.028	0.01	0.01	NS	NS

[Treatments (Spiked as concentration (ppm) in pots): T₀: 0, T₁: 1.5, T₂: 3.0, T₃: 4.5, T₄: 6.0, T₅: 7.5, T₆: 9.0, T₇: 10.5, T₈: 12.0, T₉: 13.5, T₁₀: 15.0, T₁₁: 16.5, T₁₂: 18.0, T₁₃: 19.5, T₁₄: 21.0, T₁₅: 22.5, T₁₆: 24.0]; numbers followed by different letters indicate significant differences at *p* < 0.05 (otherwise statistically at par); NS: non-significant (*p* > 0.05); (Y₀- No yellow gypsum application, Y₃₀- Yellow gypsum at 30 kg ha⁻¹, Y₆₀- Yellow gypsum at 60 kg ha⁻¹)

final volume was made up to 50 mL. In similar ways a blank and phosphorus standard was prepared and finally readings were taken in spectrophotometer at 720 nm and available phosphorus was calculated from the standard curves made from standard solutions. It is estimated by Olsen's method (15).

$$\text{Available P (mg kg}^{-1}\text{)} = (C \times V_e) / W \quad (\text{Eqn. 2})$$

Where:

C = Concentration from standard curve (mg L⁻¹)

Ve = Volume of extract (L)

W = Weight of soil (kg)

Estimation of available sulfur

Accurately weighed 10 g of soil was shaken with 50 mL 0.15 % CaCl₂ in a 250 mL conical flask for 30 min and filtered using Whatman no. 42 filter paper in polythene bottles. A 10 mL of filtrate was taken in 25 mL volumetric flasks to which 10 mL sodium acetate-acetic acid buffer (pH- 4.8) and 1 g of barium chloride crystals were added. The contents were swirled and 1 mL of 0.25 % gum acacia solution was added and finally volume was made up using distilled water. In similar ways a blank and sulphur standard were prepared and finally readings were taken in a spectrophotometer at 420 nm and available sulphur was calculated from standard curves made from standard solution (16).

$$\text{Available S (mg kg}^{-1}\text{)} = (C \times V_e) / W \quad (\text{Eqn. 3})$$

Where:

C = Concentration from standard curve

Ve = Volume of extract

W = Weight of soil

Exchangeable calcium and magnesium estimation

Accurately weighed 5 g of soil in a 100 mL conical flask was shaken with 25 mL of neutral normal ammonium acetate solution (NH₄COOCH₃) for 30 min for potassium and 5 min for rest of the elements. Then the contents were filtered through Whatman no. 42 filter paper in a plastic bottle and the clear filtrate was used for taking readings of exchangeable calcium and magnesium in an Atomic Absorption Spectrophotometer (AAS). Exchangeable Ca and Mg were analysed (17).

$$\text{Exchangeable Ca/Mg (cmol(p}^+\text{) kg}^{-1}\text{)} = (C \times V_e) / W \quad (\text{Eqn. 4})$$

Where:

C = Concentration of Ca or Mg

Ve = Volume of extract

W = Weight of soil

Estimation of available silicon

Accurately weighed 10 g of soil was shaken with 100 mL 0.01 M CaCl₂ in a 150 mL plastic bottle for 1 hr at 250 rpm and allowed to settle for 15 min and filtered using Whatman no. 42 filter paper in polythene bottles. A 10 mL of filtrate was taken in 50 mL plastic cup to which 1 mL ammonium sulfomolybdate and after 10 min 2 mL of tartaric acid solution and after 5 min 10 mL L⁻¹ ascorbic acid solutions were added. In similar ways a blank and silicon standard were prepared and finally readings were taken in a spectrophotometer at 660 nm and available silicon was calculated from standard curves made from standard solutions (18).

$$\text{Available Si (mg kg}^{-1}\text{)} = (C \times V_e) / W \quad (\text{Eqn. 5})$$

Where:

C = Concentration from standard curve

Ve = Volume of extract

W = Weight of soil

Estimation of iron and manganese

A 0.005 M DTPA (Diethylene triamine penta acetic acid) - 0.01 M CaCl₂·2H₂O- 0.1 M tri-ethanol amine solution (designated as DTPA extractant) was prepared and the pH of the solution was adjusted to 7.3. About 10 g of processed soil was shaken with 20 mL of DTPA extractant for 2 hr in a 100 mL conical flask. The contents were filtered through Whatman no. 42 filter paper in polythene bottles and the clear filtrate was used for taking readings of respective micronutrients in an Atomic Absorption Spectrophotometer (AAS) (19).

$$\text{Available Fe/Mn (mg kg}^{-1}\text{)} = (C \times V_e) / W \quad (\text{Eqn. 6})$$

Where:

C = Concentration of Fe or Mn

Ve = Volume of extract

W = Weight of soil

Percent (%) change over

Percent (%) change calculations in soil were calculated using the following equation (20):

Percent (%) change over control =

$$\frac{\text{Mean of the stage} - \text{Mean of the control (Y}_o\text{)}}{\text{Mean of the control (Y}_o\text{)}} \times 100 \quad (\text{Eqn. 7})$$

Statistical analysis

All statistical analyses were carried out using SPSS (version 7.5, 1997) and R. All measured variables were statistically analysed using methods appropriate for a factorial completely randomized design (FCRD). Duncan's multiple range test (DMRT) at 5 % was followed to compare the treatment means. A factorial CRD analysis was conducted using OPSTAT software (developed by O.P. Sheoran, CCS HAU, Hissar, Haryana) to assess the bioavailability of As across different growth stages of groundnut and boro-rice. Data presented are pooled across two seasons for each crop.

Results and Discussion

Initial soil characteristics

When the soil's initial characteristics were examined prior to groundnut crop planting, significant ($p < 0.05$) variation in each treatment's soil pH, oxidizable OC, soil available P, soil available S, soil available Si, soil exchangeable Ca and Mg was noted. However, there was no discernible difference between soil available (DTPA extractable) Fe and Mn. A range of 7.23 to 7.35 in soil pH, 5.90 to 6.23 g kg⁻¹ in OC, 11.78 to 14.24 mg kg⁻¹ available P, 45.97 to 46.11 mg kg⁻¹ available S, 28.10 to 31.99 mg kg⁻¹ available Si, 2.45 to 2.58 cmol (P⁺) kg⁻¹ exchangeable Ca, 2.18 to 2.31 cmol (P⁺) kg⁻¹ (Centimoles of proton per kilogram) exchangeable Mg, 50.93 to 51.32 mg kg⁻¹ soil available (DTPA extractable) Fe and 22.97 to 23.14 mg kg⁻¹ soil available (DTPA extractable) Mn was observed in the 17 different As-spiked soils (Table 1).

Effect of yellow gypsum on soil pH

Yellow Gypsum application significantly ($p < 0.05$) affected soil pH

during different growth stages of kharif groundnut and boro-rice crops. In kharif groundnut, soil pH increased from its initial value, ranging from 7.37–7.50 at pegging and 7.45–7.57 at harvest. The highest mean pH was recorded in T_{15} (7.47 and 7.53) and the lowest in T_1 and T_8 (7.43 and 7.50). In boro-rice, soil pH ranged from 7.39–7.51 at maximum tillering and 7.31–7.43 at harvest, with the highest values in T_{15} and T_1 (7.47 and 7.53) and the lowest in T_8 (7.35). Irrespective of treatment, Y_{60} recorded the highest mean soil pH 7.47 & 7.54 in kharif groundnut and 7.48 & 7.40 in boro-rice, while Y_0 showed the lowest 7.41 & 7.48 and 7.42 & 7.34 (Table 2). Compared to the control, Y_{60} exhibited the greatest percent increase in soil pH 0.78, 0.84 % and 0.80, 0.70 % at kharif groundnut pegging and harvest as well as at boro-rice maximum tillering and harvest respectively (Fig. 1).

Regardless of the treatment and growth stage of the component crops, the soil pH exceeded the initial level. A slight increase in soil pH was observed with increasing doses of YG over the control (Y_0), which could be attributed to the alkaline nature of the applied material. Yellow gypsum contributes S to the soil, which reacts with Fe and Al oxides or hydroxides, releasing hydroxyl (OH⁻) ions into the soil solution and thereby causing a marginal rise in soil pH (21). Similar findings were reported in an earlier study, which observed a significant increase in postharvest soil pH following YG application (22). Several studies have attributed such increases to ligand exchange between SO_4^{2-} and OH⁻ ions during soil-solution equilibration (23, 24). This exchange process likely explains the observed rise in pH following the application of YG. Other researchers have also reported that gypsum application elevates soil pH by displacing Al³⁺ and hydrogen (H⁺) ions from exchange sites into the soil solution (25–27). Similarly, the use of basic slag has been shown to significantly increase soil pH (28–30). Application of YG enhanced the concentrations of SO_4^{2-} and Ca²⁺ in the soil compared to the control. The CaSO₄ component neutralises sodium carbonate and bicarbonate, while Ca²⁺ replaces adsorbed H⁺ and sodium (Na⁺) ions, slightly increasing soil pH. However, a decrease in soil pH during the second year might be due to the removal of exchangeable cations through crop uptake. It was also reported that soil amendments such as limestone, red mud and furnace slag increase soil pH (31).

Effect of yellow gypsum on oxidisable organic carbon (g kg⁻¹)

The application of YG had a significant effect ($p < 0.05$) on soil OC content in both crops. Increasing the dosage of YG consistently enhanced soil OC at all growth stages. The OC content ranged from 5.80–6.50 g kg⁻¹ at pegging, 5.70–6.65 g kg⁻¹ at harvest of kharif groundnut, 5.70–6.73 g kg⁻¹ at maximum tillering and 5.65–6.75 g kg⁻¹ at boro-rice harvest. Among the treatments, T_2 (YG at 60 kg ha⁻¹; Y_{60}) recorded the highest mean OC values (6.30 to 6.41 g kg⁻¹ in kharif groundnut and 6.35 to 6.38 g kg⁻¹ in boro-rice), while the lowest was observed in T_6 (YG at 0 kg ha⁻¹; Y_0) 5.95 to 6.04 g kg⁻¹ at pegging stage, harvest of kharif groundnut, maximum tillering and boro-rice harvest, respectively (Table 3). Irrespective of treatment, the highest soil OC was observed with application of YG at 60 kg ha⁻¹ (Y_{60}) at pegging (6.25 g kg⁻¹), harvest of kharif groundnut (6.36 g kg⁻¹), maximum tillering (6.45 g kg⁻¹) and boro-rice harvest (6.46 g kg⁻¹). The lowest was observed in Y_0 (5.94, 5.85 and 5.82, 5.76 g kg⁻¹), respectively (Table 3). The application of Y_{60} also showed the highest percent increase in OC over the control (5.19–12.19 %) across stages (Fig. 1). The observed increase in soil OC may be attributed to

improved soil aggregation and enhanced microbial activity, resulting from gypsum-induced improvements in soil structure and nutrient availability.

Application of YG significantly increased soil oxidizable OC across all crop growth stages and at harvest, whereas a decline was observed in the control (Y_0). Over four consecutive cropping seasons, OC consistently improved in gypsum-amended plots, highlighting its role in enhancing soil carbon sequestration. This improvement may be attributed to the composition of YG, which contains substantial Ca (23.03 %) and Fe₂O₃ (5.04 %), which promote stable aggregate formation and enhance soil OC retention. Calcium facilitates the coagulation of organic matter through stable aggregate formation by acting as a bridging agent between negatively charged clay minerals and organic matter, thereby promoting the formation of stable soil aggregates and organo-mineral complexes (32, 33). This aggregation enhances the physical protection of OC within micro- and macroaggregates, thereby reducing microbial decomposition and improving SOC stabilisation (34). In addition, Ca has been reported to promote the association of organic matter with mineral surfaces, thereby increasing aggregate stability and improving overall soil structural properties (35). Improved aggregation induced by Ca amendments can also influence As immobilisation processes. Stable aggregates provide additional reactive surfaces and microenvironments that enhance the retention of arsenate (AsO₄³⁻) within mineral-associated fractions. Moreover, Ca can directly participate in geochemical stabilisation of As through precipitation or surface complexation reactions. Arsenate may react with Ca²⁺ to form relatively insoluble calcium arsenate [Ca₃(AsO₄)₂], thereby reducing As solubility and mobility in soil systems (36). Furthermore, gypsum-based amendments have been reported to decrease As bioavailability by transforming labile As into more stable soil fractions (37). Collectively, these mechanisms suggest that the application of YG can simultaneously enhance soil OC stabilisation and promote As immobilisation, thereby improving soil quality and environmental safety. These findings are consistent with the findings of previous studies (37, 38), which reported that Ca- and Fe-based amendments, such as gypsum and lime, reduce OC losses and improve the stability of soil organic matter.

Effect of yellow gypsum on soil available phosphorus (g kg⁻¹)

Application of YG had a significant effect ($p < 0.05$) on soil available P content in both crops under As-spiked treatments. Increasing the YG dosage markedly enhanced available P at all growth stages. The P content in soil ranged from 7.74–12.37 mg kg⁻¹ at pegging, 7.12–12.55 mg kg⁻¹ at harvest of kharif groundnut, 5.69–11.38 mg kg⁻¹ at maximum tillering and 5.34–10.70 mg kg⁻¹ at boro-rice harvest. The highest mean P values were recorded in T_0 and T_3 (11.65, 11.63 and 10.31, 9.68 mg kg⁻¹), while the lowest were found in T_{16} (8.40, 8.00 and 6.79, 6.39 mg kg⁻¹) at pegging, harvest of kharif groundnut, maximum tillering and boro-rice harvest, respectively (Table 4). Irrespective of treatment, the highest soil available P was observed with YG at 60 kg ha⁻¹ (Y_{60}), recording 11.16, 11.20, 10.07 and 9.47 mg kg⁻¹ at the respective stages, followed by Y_{30} , while the lowest was observed in the control (Y_0) with 9.75, 9.37, 7.86 and 7.38 mg kg⁻¹. Compared with the control, Y_{60} showed the highest percent increase in available P (14.45–28.34 %) across growth stages (Fig. 2).

A general decline in soil available P relative to the initial status was observed across treatments, indicating greater crop

Table 2. Effect of yellow gypsum on soil pH under different arsenic concentration treatments at different stages of groundnut and boro-rice crop

Treatment	Soil pH											
	Groundnut						Boro-rice					
	Pegging			Harvest			Maximum Tillering			Harvest		
	Y ₀	Y ₃₀	Y ₆₀	Mean (T)	Y ₀	Y ₃₀	Y ₆₀	Mean (T)	Y ₀	Y ₃₀	Y ₆₀	Mean (T)
T ₀	7.37	7.46	7.48	7.44 ^{bcd}	7.48	7.55	7.57	7.53 ^{abc}	7.41	7.48	7.50	7.46 ^{abc}
T ₁	7.39	7.43	7.46	7.43 ^d	7.50	7.52	7.57	7.53 ^{abc}	7.43	7.46	7.51	7.47 ^a
T ₂	7.40	7.45	7.45	7.43 ^{bcd}	7.49	7.55	7.54	7.53 ^{abcd}	7.43	7.48	7.47	7.46 ^{abc}
T ₃	7.44	7.46	7.44	7.45 ^{abcd}	7.50	7.55	7.51	7.52 ^{abcde}	7.43	7.48	7.45	7.45 ^{abc}
T ₄	7.42	7.48	7.49	7.46 ^{ab}	7.47	7.54	7.56	7.52 ^{abcde}	7.40	7.47	7.49	7.45 ^{abc}
T ₅	7.45	7.47	7.50	7.47 ^a	7.51	7.53	7.57	7.53 ^a	7.43	7.46	7.50	7.46 ^{ab}
T ₆	7.42	7.44	7.47	7.44 ^{bcd}	7.48	7.50	7.53	7.50 ^{bcd}	7.42	7.43	7.47	7.44 ^{abc}
T ₇	7.42	7.46	7.49	7.46 ^{abc}	7.49	7.52	7.55	7.52 ^{abcde}	7.43	7.45	7.48	7.45 ^{abc}
T ₈	7.40	7.42	7.46	7.43 ^d	7.47	7.49	7.54	7.50 ^{de}	7.41	7.42	7.47	7.43 ^{bc}
T ₉	7.39	7.47	7.49	7.45 ^{abcd}	7.45	7.53	7.54	7.50 ^{bcd}	7.39	7.46	7.47	7.44 ^{abc}
T ₁₀	7.40	7.44	7.46	7.43 ^{bcd}	7.46	7.50	7.53	7.50 ^e	7.40	7.43	7.47	7.43 ^c
T ₁₁	7.38	7.44	7.46	7.43 ^{bcd}	7.46	7.51	7.55	7.51 ^{abcde}	7.40	7.45	7.47	7.44 ^{abc}
T ₁₂	7.41	7.44	7.45	7.43 ^{bcd}	7.47	7.51	7.52	7.50 ^{cde}	7.42	7.45	7.46	7.44 ^{abc}
T ₁₃	7.41	7.44	7.48	7.44 ^{bcd}	7.47	7.51	7.54	7.50 ^{bcd}	7.41	7.44	7.47	7.44 ^{abc}
T ₁₄	7.43	7.45	7.46	7.45 ^{abcd}	7.50	7.52	7.54	7.52 ^{abcde}	7.44	7.46	7.48	7.46 ^{abc}
T ₁₅	7.45	7.48	7.49	7.47 ^a	7.50	7.54	7.56	7.53 ^a	7.45	7.47	7.48	7.47 ^a
T ₁₆	7.44	7.46	7.47	7.45 ^{abcd}	7.50	7.54	7.55	7.53 ^{bc}	7.44	7.47	7.48	7.46 ^{ab}
Mean (Y)	7.41 ^c	7.45 ^b	7.47 ^a		7.48 ^c	7.52 ^b	7.54 ^a		7.42 ^c	7.46 ^b	7.48 ^a	
Range		0.13				0.12				0.13		0.13
	LSD (P<0.05)	SEm ±	SE(d)		LSD (P<0.05)	SEm ±	SE(d)		LSD (P<0.05)	SEm ±	SE(d)	
T	0.008	0.003	0.004		0.01	0.003	0.004		0.009	0.003	0.004	
Y	0.004	0.001	0.002		0.004	0.001	0.002		0.004	0.001	0.002	
T*Y	0.015	0.006	0.007		0.02	0.006	0.007		0.015	0.006	0.007	

[Treatments (Spiked As Concentration (ppm) in pots): T0-0, T1-1.5, T2-3.0, T3-4.5, T4-6.0, T5-7.5, T6-9.0, T7-10.5, T8-12.0, T9-13.5, T10-15.0, T11-16.5, T12-18.0, T13-19.5, T14-21.0, T15-22.5, T16-24.0]; numbers followed by different letters indicate significant differences at $p < 0.05$ (otherwise statistically at par); NS: non-significant ($p > 0.05$); (Y₀- No yellow gypsum application, Y₃₀- Yellow gypsum at 30 kg ha⁻¹, Y₆₀- Yellow gypsum at 60 kg ha⁻¹)

Table 3. Effect of yellow gypsum on soil organic carbon under different arsenic concentration treatments at different stages of groundnut and boro-rice crop

Treatment	Groundnut										Boro-rice														
	Pegging					Harvest					Maximum Tillering					Harvest									
	Y ₀	Y ₃₀	Y ₆₀	Mean (T)	Y ₀	Y ₃₀	Y ₆₀	Mean (T)	Y ₀	Y ₃₀	Y ₆₀	Mean (T)	Y ₀	Y ₃₀	Y ₆₀	Mean (T)	Y ₀	Y ₃₀	Y ₆₀	Mean (T)					
T ₀	6.00	6.20	6.33	6.18 ^{bcd}	5.90	6.30	6.45	6.22 ^{bcd}	5.90	6.38	6.48	6.26 ^{bcd}	5.85	6.40	6.54	6.26 ^{bcd}	5.85	6.40	6.54	6.26 ^{bcd}					
T ₁	5.90	6.40	6.40	6.23 ^{abcd}	5.80	6.50	6.55	6.28 ^{abcd}	5.70	6.60	6.67	6.32 ^{abc}	5.70	6.60	6.65	6.32 ^{abc}	5.70	6.60	6.65	6.32 ^{abc}					
T ₂	6.10	6.30	6.50	6.30 ^a	6.00	6.40	6.65	6.35 ^a	6.00	6.50	6.73	6.41 ^a	5.90	6.50	6.75	6.38 ^a	5.90	6.50	6.75	6.38 ^a					
T ₃	5.90	6.14	6.14	6.06 ^{ghi}	5.80	6.20	6.27	6.09 ^{efgh}	5.75	6.32	6.32	6.13 ^{efg}	5.70	6.30	6.35	6.12 ^{efg}	5.70	6.30	6.35	6.12 ^{efg}					
T ₄	6.00	6.13	6.23	6.12 ^{efgh}	5.90	6.20	6.30	6.13 ^{efg}	5.90	6.28	6.38	6.19 ^{def}	5.80	6.30	6.40	6.17 ^{def}	5.80	6.30	6.40	6.17 ^{def}					
T ₅	6.00	6.14	6.14	6.09 ^{efgh}	5.90	6.20	6.27	6.12 ^{efg}	5.90	6.32	6.35	6.19 ^{def}	5.80	6.30	6.40	6.17 ^{def}	5.80	6.30	6.40	6.17 ^{def}					
T ₆	5.80	6.03	6.03	5.95 ^j	5.70	6.10	6.13	5.98 ^h	5.70	6.18	6.25	6.04 ^g	5.65	6.20	6.25	6.03 ^g	5.65	6.20	6.25	6.03 ^g					
T ₇	5.85	6.04	6.14	6.01 ^{hi}	5.80	6.10	6.27	6.06 ^{fgh}	5.75	6.22	6.35	6.11 ^{fg}	5.70	6.20	6.35	6.08 ^{fg}	5.70	6.20	6.35	6.08 ^{fg}					
T ₈	5.95	6.23	6.23	6.13 ^{defg}	5.90	6.30	6.30	6.17 ^{defg}	5.80	6.38	6.45	6.21 ^{bcd}	5.80	6.40	6.44	6.21 ^{bcd}	5.80	6.40	6.44	6.21 ^{bcd}					
T ₉	6.10	6.34	6.34	6.26 ^{abc}	6.00	6.40	6.40	6.27 ^{abcd}	6.00	6.52	6.52	6.34 ^{abc}	5.90	6.50	6.55	6.32 ^{abc}	5.90	6.50	6.55	6.32 ^{abc}					
T ₁₀	6.10	6.33	6.43	6.28 ^{ab}	6.00	6.40	6.50	6.30 ^{abc}	6.00	6.48	6.58	6.36 ^{ab}	5.90	6.50	6.60	6.33 ^{ab}	5.90	6.50	6.60	6.33 ^{ab}					
T ₁₁	6.10	6.34	6.34	6.26 ^{abc}	6.00	6.47	6.47	6.31 ^{ab}	6.00	6.52	6.52	6.34 ^{abc}	5.90	6.50	6.50	6.30 ^{abc}	5.90	6.50	6.50	6.30 ^{abc}					
T ₁₂	5.80	6.10	6.10	6.00 ^{hi}	5.70	6.20	6.25	6.05 ^{gh}	5.70	6.30	6.33	6.11 ^{efg}	5.65	6.30	6.35	6.10 ^{fg}	5.65	6.30	6.35	6.10 ^{fg}					
T ₁₃	5.90	6.24	6.30	6.15 ^{cdef}	5.80	6.30	6.45	6.18 ^{cdef}	5.80	6.42	6.57	6.26 ^{bcd}	5.70	6.40	6.55	6.22 ^{bcd}	5.70	6.40	6.55	6.22 ^{bcd}					
T ₁₄	5.85	6.23	6.33	6.13 ^{defg}	5.80	6.30	6.40	6.17 ^{defg}	5.70	6.38	6.48	6.19 ^{cdef}	5.70	6.40	6.50	6.20 ^{cdef}	5.70	6.40	6.50	6.20 ^{cdef}					
T ₁₅	5.80	6.20	6.14	6.05 ^{ghi}	5.70	6.30	6.25	6.08 ^{fgh}	5.70	6.40	6.32	6.14 ^{efg}	5.65	6.40	6.35	6.13 ^{efg}	5.65	6.40	6.35	6.13 ^{efg}					
T ₁₆	5.80	6.14	6.14	6.02 ^{ghi}	5.70	6.20	6.25	6.05 ^{gh}	5.70	6.32	6.35	6.12 ^{efg}	5.65	6.30	6.35	6.10 ^{fg}	5.65	6.30	6.35	6.10 ^{fg}					
Mean (Y)	5.94 ^b	6.20 ^a	6.25 ^a		5.85 ^c	6.29 ^b	6.36 ^a		5.82 ^c	6.38 ^b	6.45 ^a		5.76 ^c	6.38 ^b	6.46 ^a		5.76 ^c	6.38 ^b	6.46 ^a						
Range		0.70				0.95				1.03					1.10										
	LSD (P<0.05)					LSD (P<0.05)					LSD (P<0.05)					LSD (P<0.05)					SE(d)				
T	0.009	0.003	0.004		0.01	0.003	0.005		0.009	0.003	0.004		0.01	0.003	0.005		0.01	0.003	0.005						
Y	0.004	0.001	0.002		0.004	0.001	0.002		0.004	0.001	0.002		0.004	0.001	0.002		0.004	0.001	0.002						
T*Y	0.016	0.006	0.007		0.02	0.006	0.01		0.015	0.006	0.007		0.02	0.006	0.01		0.02	0.006	0.01						

[Treatments (Spiked As Concentration (ppm) in pots): T0-0, T1-1.5, T2-3.0, T3-4.5, T4-6.0, T5-7.5, T6-9.0, T7-10.5, T8-12.0, T9-13.5, T10-15.0, T11-16.5, T12-18.0, T13-19.5, T14-21.0, T15-22.5, T16-24.0]; numbers followed by different letters indicate significant differences at $p < 0.05$ (otherwise statistically at par); NS: non-significant ($p > 0.05$); Y₀- No yellow gypsum application, Y₃₀- Yellow gypsum at 30 kg ha⁻¹, Y₆₀- Yellow gypsum at 60 kg ha⁻¹)

Table 4. Effect of yellow gypsum on soil available phosphorus content under different arsenic concentration treatments at different stages of groundnut and boro-rice crop

Treatment	Groundnut												Boro-rice											
	Pegging						Harvest						Maximum Tillering						Harvest					
	Y ₀	Y ₃₀	Y ₆₀	Mean (T)	Y ₀	Y ₃₀	Y ₆₀	Mean (T)	Y ₀	Y ₃₀	Y ₆₀	Mean (T)	Y ₀	Y ₃₀	Y ₆₀	Mean (T)	Y ₀	Y ₃₀	Y ₆₀	Mean (T)				
T ₀	11.21	11.60	12.16	11.65 ^a	10.99	11.58	12.31	11.63 ^a	9.44	10.34	11.15	10.31 ^a	8.85	9.72	10.48	9.68 ^a								
T ₁	10.56	11.82	11.51	11.29 ^{abc}	10.26	11.83	11.58	11.22 ^{ab}	8.73	10.58	10.44	9.92 ^{ab}	8.19	9.94	9.82	9.32 ^{ab}								
T ₂	10.34	11.82	11.72	11.29 ^{abc}	10.02	11.83	11.83	11.22 ^{ab}	8.50	10.58	10.68	9.92 ^{ab}	7.97	9.94	10.04	9.32 ^{ab}								
T ₃	10.77	11.82	12.37	11.65 ^a	10.50	11.83	12.55	11.63 ^a	8.97	10.58	11.38	10.31 ^a	8.41	9.94	10.70	9.68 ^a								
T ₄	10.56	10.73	11.94	11.08 ^{bc}	10.26	10.62	12.07	10.98 ^{ab}	8.73	9.40	10.91	9.68 ^{ab}	8.19	8.84	10.26	9.10 ^{ab}								
T ₅	10.34	12.03	12.37	11.58 ^{ab}	10.02	12.07	12.55	11.55 ^a	8.50	10.81	11.38	10.23 ^a	7.97	10.16	10.70	9.61 ^a								
T ₆	10.56	10.73	11.72	11.00 ^{cd}	10.26	10.62	11.83	10.90 ^{bc}	8.73	9.40	10.68	9.60 ^{bc}	8.19	8.84	10.04	9.02 ^{bc}								
T ₇	9.69	11.16	11.94	10.93 ^{cd}	9.30	11.10	12.07	10.82 ^{bc}	7.80	9.87	10.91	9.53 ^{bc}	7.31	9.28	10.26	8.95 ^{bc}								
T ₈	10.12	11.38	12.16	11.22 ^{abc}	9.78	11.35	12.31	11.14 ^{ab}	8.26	10.11	11.15	9.84 ^{ab}	7.75	9.50	10.48	9.24 ^{ab}								
T ₉	9.69	10.95	10.86	10.50 ^{def}	9.30	10.86	10.86	10.34 ^{cde}	7.80	9.64	9.74	9.06 ^{cde}	7.31	9.06	9.16	8.51 ^{cde}								
T ₁₀	9.47	10.51	10.86	10.28 ^{efg}	9.05	10.37	10.86	10.09 ^{def}	7.56	9.17	9.74	8.82 ^{def}	7.10	8.62	9.16	8.29 ^{def}								
T ₁₁	10.12	10.73	11.51	10.79 ^{de}	9.78	10.61	11.58	10.66 ^{bcd}	8.26	9.40	10.44	9.36 ^{bcd}	7.75	8.84	9.82	8.80 ^{bcd}								
T ₁₂	9.26	10.08	10.86	10.06 ^{fg}	8.81	9.89	10.86	9.85 ^{ef}	7.33	8.70	9.74	8.59 ^{ef}	6.88	8.18	9.16	8.07 ^{ef}								
T ₁₃	9.04	9.86	10.64	9.85 ^g	8.57	9.65	10.61	9.61 ^f	7.09	8.46	9.50	8.35 ^f	6.66	7.96	8.94	7.85 ^f								
T ₁₄	8.39	9.43	9.34	9.05 ^h	7.84	9.16	9.16	8.72 ^g	6.39	7.99	8.10	7.49 ^g	6.00	7.52	7.63	7.05 ^g								
T ₁₅	7.95	8.99	8.91	8.62 ^{hi}	7.36	8.68	8.68	8.24 ^{gh}	5.92	7.52	7.63	7.03 ^{gh}	5.56	7.08	7.19	6.61 ^{gh}								
T ₁₆	7.74	8.56	8.91	8.40 ⁱ	7.12	8.19	8.68	8.00 ^h	5.69	7.06	7.63	6.79 ^h	5.34	6.64	7.19	6.39 ^h								
Mean (Y)	9.75 ^c	10.72 ^b	11.16 ^a		9.37 ^c	10.60 ^b	11.20 ^a		7.86 ^c	9.39 ^b	10.07 ^a		7.38 ^c	8.83 ^b	9.47 ^a									
Range		4.64				5.44				5.69					5.36									
	LSD (p<0.05)	SEm ±	SE(d)		LSD (p<0.05)	SEm ±	SE(d)		LSD (p<0.05)	SEm ±	SE(d)		LSD (p<0.05)	SEm ±	SE(d)									
T	0.01	0.004	0.01		0.01	0.004	0.004		0.009	0.003	0.01		0.01	0.003	0.004									
Y	0.005	0.002	0.002		0.005	0.002	0.002		0.004	0.001	0.002		0.004	0.001	0.002									
T*Y	0.02	0.01	0.01		0.02	0.01	0.006		0.016	0.006	0.01		0.01	0.005	0.007									

[Treatments (Spiked as concentration (ppm) in pots]: T₀: 0, T₁: 1.5, T₂: 3.0, T₃: 4.5, T₄: 6.0, T₅: 7.5, T₆: 9.0, T₇: 10.5, T₈: 12.0, T₉: 13.5, T₁₀: 15.0, T₁₁: 16.5, T₁₂: 18.0, T₁₃: 19.5, T₁₄: 21.0, T₁₅: 22.5, T₁₆: 24.0; numbers followed by different letters indicate significant differences at p < 0.05 (otherwise statistically at par); NS: non-significant (p > 0.05); (Y₀- No yellow gypsum application, Y₃₀- Yellow gypsum at 30 kg ha⁻¹, Y₆₀- Yellow gypsum at 60 kg ha⁻¹)

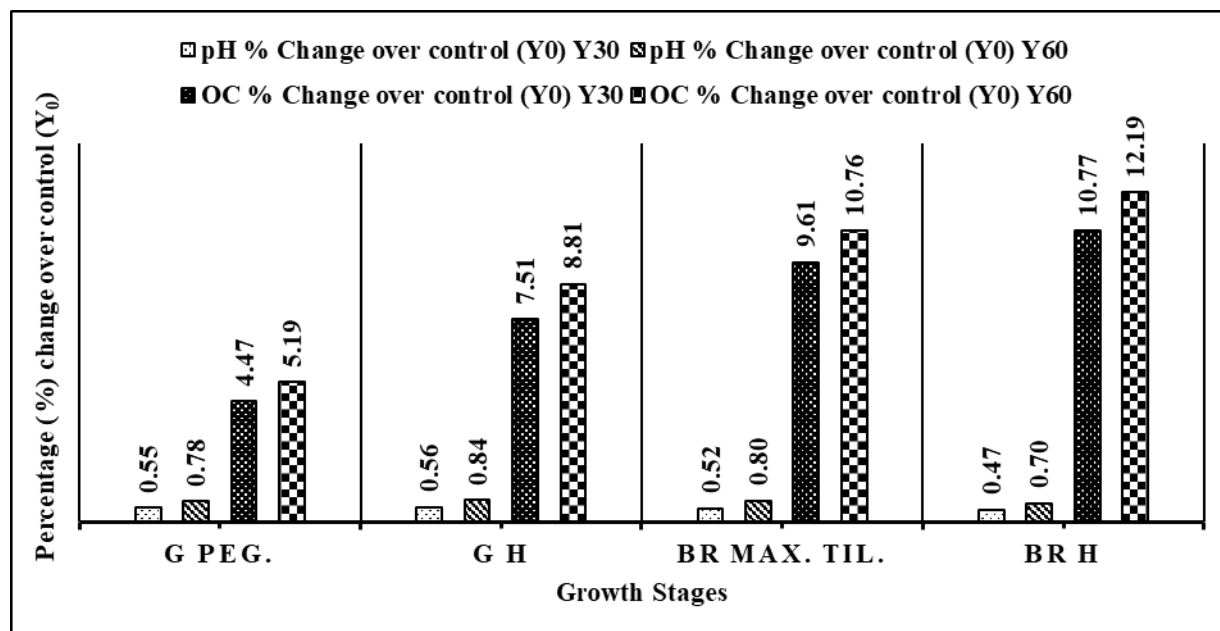


Fig. 1. Percent change in soil pH and organic carbon after application of yellow gypsum in groundnut and boro-rice crop. (Y₀: No yellow gypsum application; Y₃₀: Yellow gypsum at 30 kg ha⁻¹; Y₆₀: Yellow gypsum at 60 kg ha⁻¹)

uptake. However, the application of YG consistently increased P availability across all As levels compared to the control. This improvement can be attributed to the release of sulfate (SO₄²⁻) ions from gypsum, which interact with adsorbed phosphate (PO₄³⁻), promoting its desorption into the soil solution. In addition, YG supplies soluble Si, which reduces P fixation by competing for adsorption sites, thereby increasing P availability (39). The presence of monosilicic acid in soil solution further facilitates the conversion of less soluble P forms into plant-available forms (40).

Over four cropping seasons, an inverse relationship was evident between soil extractable As and available P, with a decline in As coinciding with increased P availability. This pattern is primarily governed by competitive sorption between PO₄³⁻ and AsO₄³⁻, as both anions share similar chemical properties and compete for binding sites on soil colloids and Fe/aluminum oxides (41). Their comparable dissociation constants, structural configuration and nearly identical ionic radii enable PO₄³⁻ to effectively displace AsO₄³⁻ from sorption sites (38). This competitive interaction is further influenced by soil properties such as pH, redox potential, Fe/Al oxide content, P application rate and crop genotype (42). Consequently, PO₄³⁻ addition can increase As mobility by releasing it into the soil solution, thereby enhancing its potential for leaching (43).

Arsenic behavior in soils is strongly influenced by its interaction with P because AsO₄³⁻ and PO₄³⁻ have similar molecular structures and compete for adsorption sites on soil minerals, particularly Fe and aluminum oxides. This competitive sorption plays a critical role in regulating As mobility, speciation and bioavailability in soils. Phosphate can displace AsO₄³⁻ from mineral surfaces due to their analogous chemical behavior, thereby affecting As retention and transport processes in soil systems (35). In the present study, the application of YG reduced As availability, suggesting that the amendment influenced soil geochemical processes responsible for As stabilization. The alkaline nature of YG and the presence of Ca may enhance As immobilization through adsorption and precipitation reactions, including the formation of relatively stable Ca₃(AsO₄)₂ complexes. Moreover, AsO₄³⁻ enters plant roots via PO₄³⁻ transporters; therefore, adequate P supply can competitively suppress As uptake and accumulation in plants

(44, 45). These combined mechanisms indicate that YG amendment can effectively reduce As mobility and plant availability in contaminated soils.

Effect of yellow gypsum on soil available sulfur

Application of increasing levels of YG significantly ($p < 0.05$) enhanced the available S content in soil across all treatments in both crops. The S content ranged from 38.85–44.15 and 37.04–43.82 mg kg⁻¹ at pegging and harvest of kharif groundnut and from 33.73–42.90 and 31.90–42.64 mg kg⁻¹ at maximum tillering and boro-rice harvest, respectively. The highest mean S content was recorded in treatment T₅, while the lowest was in T₁₆ (Table 5). A slight increase in soil S was observed with decreasing soil As levels throughout the four cropping seasons. Among the gypsum levels, application of YG at 60 kg ha⁻¹ (Y₆₀) recorded the highest S content (43.84, 43.46, 42.49 and 42.19 mg kg⁻¹), followed by Y₃₀, whereas the lowest was in the control (Y₀) with 39.01, 37.23, 34.02 and 32.27 mg kg⁻¹ (Table 5). The Y₆₀ treatment showed the highest percent increase in available S (12.38, 16.75 and 24.90, 30.71 %) over control across the growth stages (Fig. 2).

There was a decrease in the soil's S content relative to its initial level. Reduced soil S availability indicates that the crop is removing more S than is needed for growth. Due to the release of S from the applied YG, which contains an adequate quantity of S (17.38 %) (10) and the high solubility nature of gypsum (46, 47), the amount of S available in the soil was higher when compared to control treatments. The application of YG was found to marginally raise the pH of the soil (> 7) in our investigation, which in turn raised the amount of S available in the soil. According to previously conducted studies, SO₄²⁻ ion adsorption on positively charged sites in a soil matrix declined as soil pH increased; at pH values above 6, adsorption was essentially negligible (46, 48). The competition for soil anion sorption sites between SiO₃²⁻ and YG increased upon addition of YG (49). Additionally, adding slag-based materials to soils increased the concentration of PO₄³⁻ ions in the soil solution, thereby increasing the amount of S available in the soil. The application of YG may therefore contribute to increased S availability in soils, both directly as a source of S and indirectly (22).

Table 5. Effect of yellow gypsum on soil available sulfur content under different arsenic concentration treatments at different stages of groundnut and boro-rice crop

Treatment	Groundnut										Boro-rice									
	Pegging					Harvest					Maximum tillering					Harvest				
	Y ₀	Y ₃₀	Y ₆₀	Mean (T)	Y ₀	Y ₃₀	Y ₆₀	Mean (T)	Y ₀	Y ₃₀	Y ₆₀	Mean (T)	Y ₀	Y ₃₀	Y ₆₀	Mean (T)	Y ₀	Y ₃₀	Y ₆₀	Mean (T)
T ₀	39.03	41.31	44.03	41.45 ^{ab}	37.27	40.22	43.69	40.39 ^{ab}	34.09	38.16	42.77	38.34 ^a	32.37	37.14	42.50	37.34 ^a	32.37	37.14	42.50	37.34 ^a
T ₁	39.00	41.24	43.99	41.41 ^{ab}	37.24	40.16	43.66	40.35 ^{ab}	34.06	38.09	42.74	38.30 ^{ab}	32.34	37.07	42.47	37.29 ^{ab}	32.34	37.07	42.47	37.29 ^{ab}
T ₂	39.09	41.27	44.03	41.46 ^{ab}	37.33	40.19	43.69	40.40 ^{ab}	34.16	38.13	42.77	38.35 ^a	32.44	37.10	42.50	37.35 ^a	32.44	37.10	42.50	37.35 ^a
T ₃	39.03	41.31	44.05	41.46 ^{ab}	37.27	40.22	43.73	40.40 ^{ab}	34.09	38.16	42.80	38.35 ^a	32.37	37.14	42.53	37.35 ^a	32.37	37.14	42.53	37.35 ^a
T ₄	39.00	41.24	44.03	41.42 ^{ab}	37.24	40.16	43.69	40.36 ^{ab}	34.06	38.09	42.77	38.31 ^{ab}	32.34	37.07	42.50	37.30 ^{ab}	32.34	37.07	42.50	37.30 ^{ab}
T ₅	39.15	41.37	44.12	41.54 ^a	37.39	40.28	43.79	40.49 ^a	34.22	38.22	42.87	38.44 ^a	32.50	37.20	42.60	37.44 ^a	32.50	37.20	42.60	37.44 ^a
T ₆	39.09	41.31	44.05	41.48 ^{ab}	37.33	40.22	43.73	40.42 ^{ab}	34.16	38.16	42.80	38.37 ^a	32.44	37.14	42.53	37.37 ^a	32.44	37.14	42.53	37.37 ^a
T ₇	39.12	41.34	44.08	41.51 ^a	37.36	40.25	43.76	40.45 ^a	34.19	38.19	42.84	38.40 ^a	32.47	37.17	42.57	37.40 ^a	32.47	37.17	42.57	37.40 ^a
T ₈	38.97	41.24	43.99	41.40 ^{ab}	37.20	40.16	43.66	40.34 ^{ab}	34.03	38.09	42.74	38.29 ^{ab}	32.30	37.07	42.47	37.28 ^{ab}	32.30	37.07	42.47	37.28 ^{ab}
T ₉	39.09	41.40	44.15	41.54 ^a	37.33	40.31	43.82	40.49 ^a	34.16	38.25	42.90	38.44 ^a	32.44	37.24	42.64	37.44 ^a	32.44	37.24	42.64	37.44 ^a
T ₁₀	39.12	41.10	43.63	41.28 ^{bc}	37.36	39.97	43.25	40.19 ^{bc}	34.19	37.83	42.24	38.09 ^{bc}	32.47	36.80	41.95	37.07 ^{bc}	32.47	36.80	41.95	37.07 ^{bc}
T ₁₁	39.01	41.02	43.58	41.20 ^{cd}	37.23	39.87	43.18	40.09 ^{cd}	34.02	37.73	42.17	37.97 ^{cd}	32.27	36.67	41.85	36.93 ^{cd}	32.27	36.67	41.85	36.93 ^{cd}
T ₁₂	38.96	41.01	43.50	41.16 ^{cd}	37.17	39.84	43.09	40.03 ^{cd}	33.96	37.70	42.07	37.91 ^{cde}	32.17	36.60	41.72	36.83 ^{cde}	32.17	36.60	41.72	36.83 ^{cde}
T ₁₃	38.85	40.99	43.55	41.13 ^{cd}	37.04	39.81	43.12	39.99 ^{cd}	33.76	37.63	42.07	37.82 ^{de}	31.97	36.53	41.71	36.73 ^{de}	31.97	36.53	41.71	36.73 ^{de}
T ₁₄	38.88	41.05	43.58	41.17 ^{cd}	37.07	39.87	43.15	40.03 ^{cd}	33.79	37.69	42.10	37.86 ^{cde}	32.00	36.59	41.75	36.78 ^{cde}	32.00	36.59	41.75	36.78 ^{cde}
T ₁₅	38.88	40.91	43.43	41.07 ^d	37.04	39.68	42.95	39.89 ^d	33.73	37.46	41.86	37.68 ^e	31.90	36.29	41.43	36.54 ^e	31.90	36.29	41.43	36.54 ^e
T ₁₆	38.88	40.88	43.43	41.06 ^d	37.04	39.64	42.95	39.88 ^d	33.73	37.43	41.86	37.67 ^e	31.90	36.26	41.43	36.53 ^e	31.90	36.26	41.43	36.53 ^e
Mean (Y)	39.01 ^c	41.17 ^b	43.84 ^a		37.23 ^c	40.05 ^b	43.46 ^a		34.02 ^c	37.94 ^b	42.49 ^a		32.27 ^c	36.89 ^b	42.19 ^a		32.27 ^c	36.89 ^b	42.19 ^a	
Range		5.29				6.79				9.18					10.75					
T	LSD (P<0.05)					SEm ±					LSD (P<0.05)					SEm ±				
	0.04					0.01					0.04					0.01				
Y	0.02					0.01					0.02					0.01				
T*Y	0.07					0.02					0.06					0.02				

[Treatments (Spiked as concentration (ppm) in pots): T₀: 0, T₁: 1.5, T₂: 3.0, T₃: 4.5, T₄: 6.0, T₅: 7.5, T₆: 9.0, T₇: 10.5, T₈: 12.0, T₉: 13.5, T₁₀: 15.0, T₁₁: 16.5, T₁₂: 18.0, T₁₃: 19.5, T₁₄: 21.0, T₁₅: 22.5, T₁₆: 24.0]; numbers followed by different letters indicate significant differences at $p < 0.05$ (otherwise statistically at par); NS: non-significant ($p > 0.05$); (Y₀: No yellow gypsum application, Y₃₀: Yellow gypsum at 30 kg ha⁻¹, Y₆₀: Yellow gypsum at 60 kg ha⁻¹)

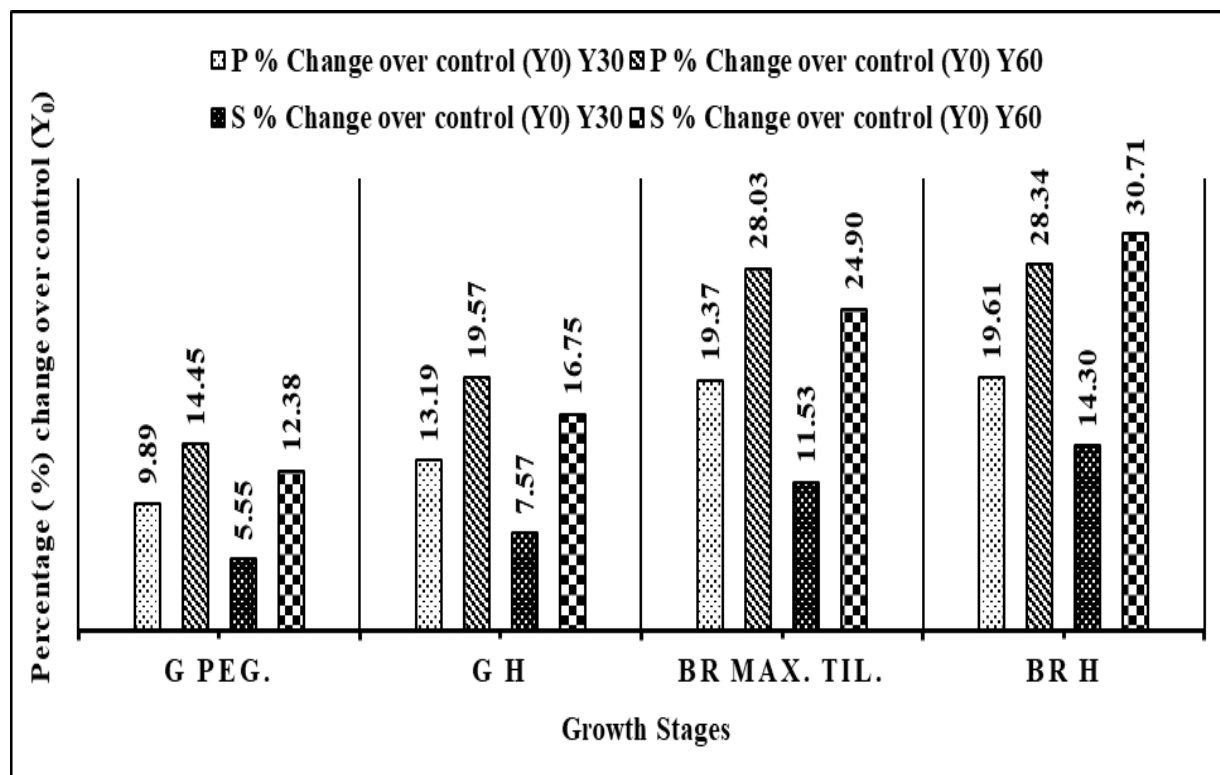


Fig. 2. Percent change in soil available phosphorus and sulfur after application of yellow gypsum in groundnut and boro-rice crop. (Y₀: No yellow gypsum application; Y₃₀: Yellow gypsum at 30 kg ha⁻¹; Y₆₀: Yellow gypsum at 60 kg ha⁻¹)

Effect of yellow gypsum on soil available silicon

The application of YG significantly increased soil-available Si across all treatments ($p < 0.05$). The Si content ranged from 20.80–29.74, 19.70–28.57, 15.32–25.36 and 14.01–24.75 mg kg⁻¹ at pegging, harvest of kharif groundnut, maximum tillering and boro-rice harvest, respectively. The highest mean Si was observed in T₂ and the lowest in T₁₆, with 28.14–21.99, 26.96–20.90, 23.43–16.92 and 22.65–15.80 mg kg⁻¹ at respective stages. Soil available Si showed a declining trend with increasing As levels, indicating an inverse relation with extractable As throughout the four cropping seasons. Application of YG at 60 kg ha⁻¹ (Y₆₀) recorded the highest Si (26.82, 25.71, 22.43 and 21.72 mg kg⁻¹), followed by Y₃₀, while the lowest was in control (Y₀) (Table 6). The percent increase in Si over control in Y₆₀ ranged from 11.60, 12.31 and 18.37, 21.37 % across all stages (Fig. 3).

There was a decrease in the soil's Si content relative to its initial level. The crop must remove more Si to grow, as indicated by the decline in soil-accessible Si. The mean soil Si content during both crop growth phases and at harvest increased with the application of YG. Because YG may release silica into the soil, its application increased the amount of readily available Si in the soil compared with control treatments. However, applying YG also increased the amount of Si available in the soil by speeding up the conversion of amorphous Si to soluble Si (50). The increase in soil pH encourages the release of colloid-adsorbed Si to the soil solution (51) and advances the transformation of polysilicic acid into monosilicic acid (52). The findings were consistent with those of a previously conducted investigation, which reported that plant-available Si increased with increasing levels of YG (53).

Effect of yellow gypsum on soil exchangeable calcium and magnesium

Yellow Gypsum serves as an effective source of Ca and demonstrated a significant ($p < 0.05$) effect on increasing soil Ca content; however, it did not produce a significant change in soil Mg

content. The Ca content in soil ranged from 2.24 to 2.54 cmol (P⁺) kg⁻¹ at pegging, 2.17 to 2.53 cmol (P⁺) kg⁻¹ at harvest of kharif groundnut, 2.09 to 2.49 cmol (P⁺) kg⁻¹ at maximum tillering and 2.03 to 2.42 cmol (P⁺) kg⁻¹ at boro-rice harvest. The highest mean soil Ca was recorded in T₀ and the lowest in T₁₆ at all growth stages, with values decreasing proportionally with increasing As concentration, indicating an inverse relationship between exchangeable Ca and extractable As throughout the 4 cropping seasons (Table 7).

Soil exchangeable Mg ranged between 1.98–2.13, 2.00–2.15, 1.86–2.01 and 1.88–2.03 cmol (P⁺) kg⁻¹ at pegging, harvest of kharif groundnut, maximum tillering and boro-rice harvest, respectively, showing a narrow variation (0.15 cmol (P⁺) kg⁻¹). The highest mean Mg was found in T₆, while the lowest was in T₅. Application of YG at 60 kg ha⁻¹ (Y₆₀) resulted in the highest Ca contents (2.46, 2.44, 2.40 and 2.34 cmol (P⁺) kg⁻¹), followed by Y₃₀, whereas the lowest values were recorded in the control (Y₀) (2.31, 2.24, 2.16 and 2.10 cmol (P⁺) kg⁻¹) at the respective stages. Magnesium levels remained statistically similar among Y₀, Y₃₀ and Y₆₀ treatments, suggesting minimal influence of YG on soil Mg status (Table 8).

Compared to the control, Y₆₀ showed the highest percent increase in Ca (6.54, 8.92, 11.48 and 11.50 %) at pegging, harvest of kharif groundnut, maximum tillering and boro-rice harvest, respectively (Fig. 4). Overall, a decline in both Ca and Mg relative to their initial levels indicated crop uptake during growth. While Ca content improved with reduced As concentration, Mg remained largely unaffected, highlighting differential nutrient behavior under As stress and gypsum application.

Applying YG, a major source of Ca with 23.03 % Ca, increased the amount of Ca available in the soil compared to the control treatment (10). Calcium plays an important role in regulating As mobility and stabilization in soils, particularly in systems amended with Ca-rich materials such as gypsum. Under aerobic soil conditions, As predominantly occurs as AsO₄³⁻, which can interact

Table 6. Effect of yellow gypsum on soil available silicon content under different arsenic concentration treatments at different stages of groundnut and boro-rice crop

Treatment	Groundnut										Boro-rice									
	Pegging					Harvest					Maximum tillering					Harvest				
	Available Silicon (mg kg ⁻¹)																			
	Y ₀	Y ₃₀	Y ₆₀	Mean (T)	Y ₀	Y ₃₀	Y ₆₀	Mean (T)	Y ₀	Y ₃₀	Y ₆₀	Mean (T)	Y ₀	Y ₃₀	Y ₆₀	Mean (T)	Y ₀	Y ₃₀	Y ₆₀	Mean (T)
T ₀	26.05	27.90	29.39	27.78 ^{ab}	24.89	26.73	28.22	26.61 ^{ab}	21.07	23.22	25.04	23.11 ^a	20.12	22.44	24.44	23.11 ^a	20.12	22.44	24.44	22.33 ^a
T ₁	25.70	26.82	28.67	27.06 ^c	24.54	25.69	27.53	25.92 ^c	20.75	22.26	24.41	22.47 ^b	19.81	21.49	23.81	22.47 ^b	19.81	21.49	23.81	21.70 ^b
T ₂	26.77	27.90	29.74	28.14 ^a	25.58	26.73	28.57	26.96 ^a	21.71	23.22	25.36	23.43 ^a	20.75	22.44	24.75	23.43 ^a	20.75	22.44	24.75	22.65 ^a
T ₃	24.98	26.46	28.30	26.58 ^c	23.84	25.34	27.19	25.46 ^c	20.12	21.94	24.09	22.05 ^b	19.17	21.17	23.49	22.05 ^b	19.17	21.17	23.49	21.28 ^b
T ₄	25.33	26.82	28.30	26.82 ^c	24.19	25.69	27.19	25.69 ^c	20.43	22.26	24.09	22.26 ^b	19.49	21.49	23.49	22.26 ^b	19.49	21.49	23.49	21.49 ^b
T ₅	26.05	27.90	29.02	27.66 ^b	24.89	26.73	27.88	26.50 ^b	21.07	23.22	24.72	23.00 ^a	20.12	22.44	24.12	23.00 ^a	20.12	22.44	24.12	22.23 ^a
T ₆	25.33	26.10	28.30	26.58 ^c	24.19	24.99	27.19	25.46 ^c	20.43	21.62	24.09	22.05 ^b	19.49	20.86	23.49	22.05 ^b	19.49	20.86	23.49	21.28 ^b
T ₇	25.33	26.46	28.30	26.70 ^c	24.19	25.34	27.19	25.57 ^c	20.43	21.94	24.09	22.15 ^b	19.49	21.17	23.49	22.15 ^b	19.49	21.17	23.49	21.38 ^b
T ₈	24.98	26.82	28.30	26.70 ^c	23.84	25.69	27.19	25.57 ^c	20.12	22.26	24.09	22.15 ^b	19.17	21.49	23.49	22.15 ^b	19.17	21.49	23.49	21.38 ^b
T ₉	23.92	25.22	26.77	25.30 ^d	22.75	24.07	25.63	24.15 ^d	18.94	20.49	22.41	20.61 ^c	17.94	19.61	21.72	20.61 ^c	17.94	19.61	21.72	19.76 ^c
T ₁₀	23.67	24.50	25.44	24.54 ^e	22.52	23.38	24.36	23.42 ^e	18.57	19.85	21.08	19.83 ^d	17.51	18.98	20.34	19.83 ^d	17.51	18.98	20.34	18.94 ^d
T ₁₁	22.95	24.14	25.08	24.06 ^f	21.83	23.03	24.01	22.96 ^f	17.93	19.53	20.76	19.41 ^e	16.87	18.66	20.02	19.41 ^e	16.87	18.66	20.02	18.52 ^e
T ₁₂	22.35	23.90	25.20	23.81 ^f	21.25	22.81	24.13	22.73 ^f	17.24	19.16	20.71	19.04 ^e	16.12	18.23	19.90	19.04 ^e	16.12	18.23	19.90	18.08 ^f
T ₁₃	21.41	22.84	24.14	22.80 ^g	20.27	21.71	23.03	21.67 ^g	16.01	17.99	19.53	17.84 ^f	14.76	17.00	18.66	17.84 ^f	14.76	17.00	18.66	16.81 ^g
T ₁₄	21.41	22.60	23.90	22.63 ^g	20.27	21.48	22.81	21.52 ^g	16.01	17.61	19.16	17.59 ^f	14.76	16.56	18.23	17.59 ^f	14.76	16.56	18.23	16.52 ^g
T ₁₅	21.52	22.71	23.90	22.71 ^g	20.39	21.60	22.81	21.60 ^g	15.96	17.56	19.16	17.56 ^f	14.64	16.43	18.23	17.56 ^f	14.64	16.43	18.23	16.43 ^g
T ₁₆	20.80	21.99	23.18	21.99 ^h	19.70	20.90	22.11	20.90 ^h	15.32	16.92	18.52	16.92 ^g	14.01	15.80	17.59	16.92 ^g	14.01	15.80	17.59	15.80 ^h
Mean (Y)	24.03 ^c	25.36 ^b	26.82 ^a		22.89 ^c	24.23 ^b	25.71 ^a		18.95 ^c	20.65 ^b	22.43 ^a		17.90 ^c	19.78 ^b	21.72 ^a		17.90 ^c	19.78 ^b	21.72 ^a	
Range		8.94				8.88				10.04				10.75						
T	LSD (P<0.05)	SEM ±	SE(d)		LSD (P<0.05)	SEM ±	SE(d)		LSD (P<0.05)	SEM ±	SE(d)		LSD (P<0.05)	SEM ±	SE(d)		LSD (P<0.05)	SEM ±	SE(d)	
Y	0.02	0.01	0.01		0.02	0.01	0.01		0.02	0.01	0.01		0.02	0.01	0.01		0.02	0.01	0.01	
T*Y	0.01	0.004	0.005		0.01	0.004	0.01		0.01	0.003	0.004		0.01	0.003	0.004		0.01	0.003	0.004	
	0.04	0.01	0.02		0.04	0.01	0.02		0.03	0.01	0.02		0.03	0.01	0.02		0.03	0.01	0.02	

[Treatments (Spiked as concentration (ppm) in pots): T₀: 0, T₁: 1.5, T₂: 3.0, T₃: 4.5, T₄: 6.0, T₅: 7.5, T₆: 9.0, T₇: 10.5, T₈: 12.0, T₉: 13.5, T₁₀: 15.0, T₁₁: 16.5, T₁₂: 18.0, T₁₃: 19.5, T₁₄: 21.0, T₁₅: 22.5, T₁₆: 24.0]; numbers followed by different letters indicate significant differences at p < 0.05 (otherwise statistically at par); NS: non-significant (p > 0.05); (Y₀: No yellow gypsum application, Y₃₀: Yellow gypsum at 30 kg ha⁻¹, Y₆₀: Yellow gypsum at 60 kg ha⁻¹)

Table 7. Effect of yellow gypsum on soil exchangeable calcium content under different arsenic concentration treatments at different stages of groundnut and boro-rice crop

Treatment	Available Calcium [cmol (P ⁺) kg ⁻¹]															
	Groundnut						Boro-rice									
	Pegging			Harvest			Maximum tillering				Harvest					
	Y ₀	Y ₃₀	Y ₆₀	Mean (T)	Y ₀	Y ₃₀	Y ₆₀	Mean (T)	Y ₀	Y ₃₀	Y ₆₀	Mean (T)	Y ₀	Y ₃₀	Y ₆₀	Mean (T)
T ₀	2.36	2.45	2.54	2.45 ^a	2.30	2.42	2.53	2.41 ^a	2.21	2.36	2.49	2.35 ^a	2.15	2.30	2.42	2.29 ^a
T ₁	2.33	2.43	2.47	2.41 ^{cd}	2.27	2.39	2.45	2.37 ^{cd}	2.18	2.34	2.41	2.31 ^{cd}	2.12	2.27	2.35	2.25 ^{cd}
T ₂	2.34	2.44	2.51	2.43 ^b	2.27	2.40	2.49	2.39 ^b	2.18	2.35	2.45	2.33 ^b	2.12	2.28	2.39	2.26 ^b
T ₃	2.34	2.40	2.47	2.40 ^{cd}	2.28	2.37	2.45	2.36 ^{cd}	2.19	2.31	2.41	2.30 ^{cd}	2.13	2.25	2.35	2.24 ^{cd}
T ₄	2.33	2.43	2.50	2.42 ^{bc}	2.26	2.40	2.48	2.38 ^{bc}	2.17	2.34	2.44	2.32 ^{bc}	2.12	2.28	2.37	2.26 ^{bc}
T ₅	2.34	2.43	2.49	2.42 ^{bc}	2.27	2.39	2.47	2.38 ^{bc}	2.18	2.34	2.43	2.32 ^{bc}	2.13	2.28	2.37	2.26 ^{bc}
T ₆	2.32	2.41	2.47	2.40 ^d	2.26	2.37	2.45	2.36 ^d	2.17	2.32	2.42	2.30 ^d	2.11	2.26	2.35	2.24 ^d
T ₇	2.32	2.40	2.47	2.40 ^d	2.26	2.37	2.45	2.36 ^d	2.17	2.31	2.41	2.30 ^d	2.11	2.25	2.35	2.24 ^d
T ₈	2.33	2.41	2.49	2.41 ^{cd}	2.26	2.38	2.47	2.37 ^{cd}	2.17	2.33	2.43	2.31 ^{cd}	2.11	2.26	2.37	2.25 ^{cd}
T ₉	2.30	2.39	2.44	2.38 ^e	2.24	2.35	2.43	2.34 ^e	2.15	2.29	2.39	2.28 ^e	2.09	2.23	2.32	2.21 ^e
T ₁₀	2.30	2.38	2.45	2.37 ^e	2.23	2.34	2.43	2.33 ^e	2.15	2.29	2.39	2.27 ^e	2.09	2.22	2.32	2.21 ^e
T ₁₁	2.29	2.38	2.45	2.37 ^e	2.22	2.35	2.43	2.33 ^e	2.14	2.29	2.39	2.27 ^e	2.08	2.23	2.33	2.21 ^e
T ₁₂	2.31	2.38	2.45	2.38 ^e	2.24	2.35	2.43	2.34 ^e	2.15	2.29	2.39	2.28 ^e	2.10	2.23	2.32	2.22 ^e
T ₁₃	2.26	2.35	2.42	2.35 ^f	2.20	2.32	2.40	2.31 ^f	2.11	2.26	2.37	2.25 ^f	2.05	2.20	2.30	2.18 ^f
T ₁₄	2.27	2.35	2.41	2.34 ^f	2.20	2.31	2.39	2.30 ^f	2.11	2.26	2.35	2.24 ^f	2.06	2.19	2.29	2.18 ^f
T ₁₅	2.26	2.35	2.41	2.34 ^f	2.20	2.31	2.40	2.30 ^f	2.11	2.26	2.36	2.24 ^f	2.05	2.20	2.29	2.18 ^f
T ₁₆	2.24	2.31	2.37	2.31 ^g	2.17	2.27	2.36	2.27 ^g	2.09	2.22	2.32	2.21 ^g	2.03	2.16	2.26	2.15 ^g
Mean (Y)	2.31 ^c	2.39 ^b	2.46 ^a		2.24 ^c	2.36 ^b	2.44 ^a		2.16 ^c	2.30 ^b	2.40 ^a		2.10 ^c	2.24 ^b	2.34 ^a	
Range		0.31				0.36				0.40				0.39		
T	LSD (p<0.05)			SEm ±	SE(d)	LSD (p<0.05)			SEm ±	SE(d)	LSD (p<0.05)			SEm ±	SE(d)	
Y	0.005	0.002	0.002		0.004	0.001	0.002		0.005	0.002	0.002		0.003	0.001	0.002	
Y	0.002	0.001	0.001		0.002	0.001	0.001		0.002	0.001	0.001		0.001	0.001	0.001	
T*Y	0.008	0.003	0.004		0.01	0.0025	0.004		0.008	0.003	0.004		0.006	0.002	0.003	

[Treatments (Spiked as concentration (ppm) in pots): T₀: 0, T₁: 1.5, T₂: 3.0, T₃: 4.5, T₄: 6.0, T₅: 7.5, T₆: 9.0, T₇: 10.5, T₈: 12.0, T₉: 13.5, T₁₀: 15.0, T₁₁: 16.5, T₁₂: 18.0, T₁₃: 19.5, T₁₄: 21.0, T₁₅: 22.5, T₁₆: 24.0]; numbers followed by different letters indicate significant differences at p < 0.05 (otherwise statistically at par); NS: non-significant (p > 0.05); (Y₀: No yellow gypsum application, Y₃₀: Yellow gypsum at 30 kg ha⁻¹, Y₆₀: Yellow gypsum at 60 kg ha⁻¹)

Table 8. Effect of yellow gypsum on soil exchangeable Magnesium content under different arsenic concentration treatments at different stages of groundnut and boro-rice crop

Treatment	Groundnut										Boro-rice									
	Pegging					Harvest					Maximum tillering					Harvest				
	Y ₀	Y ₃₀	Y ₆₀	Mean (T)	Y ₀	Y ₃₀	Y ₆₀	Mean (T)	Y ₀	Y ₃₀	Y ₆₀	Mean (T)	Y ₀	Y ₃₀	Y ₆₀	Mean (T)	Y ₀	Y ₃₀	Y ₆₀	Mean (T)
T ₀	2.07	2.08	2.10	2.08 ^b	2.09	2.10	2.12	2.10 ^b	1.95	1.97	1.98	1.96 ^b	1.96	1.98	2.00	1.96 ^b	1.96	1.98	2.00	1.98 ^b
T ₁	1.99	2.05	2.01	2.02 ^{fg}	2.01	2.08	2.03	2.04 ^{def}	1.87	1.93	1.90	1.90 ^{ghi}	1.89	1.95	1.92	1.90 ^{ghi}	1.89	1.95	1.92	1.92 ^{fg}
T ₂	2.05	2.06	2.07	2.06 ^{cd}	2.07	2.08	2.09	2.08 ^{bc}	1.92	1.94	1.95	1.94 ^{cde}	1.94	1.96	1.97	1.94 ^{cde}	1.94	1.96	1.97	1.96 ^{cd}
T ₃	2.03	2.03	2.03	2.03 ^{ef}	2.05	2.06	2.06	2.05 ^{de}	1.93	1.92	1.92	1.92 ^{efg}	1.93	1.93	1.94	1.92 ^{efg}	1.93	1.93	1.94	1.93 ^{ef}
T ₄	1.98	1.99	1.99	1.98 ⁱ	2.00	2.01	2.01	2.01 ^g	1.86	1.87	1.88	1.87 ^j	1.88	1.89	1.90	1.87 ^j	1.88	1.89	1.90	1.89 ^h
T ₅	2.09	2.13	2.13	2.11 ^a	2.11	2.15	2.15	2.14 ^a	1.96	2.01	2.01	1.99 ^a	1.98	2.03	2.03	1.99 ^a	1.98	2.03	2.03	2.01 ^a
T ₆	2.00	2.04	2.01	2.01 ^{gh}	2.02	2.06	2.03	2.04 ^{ef}	1.88	1.92	1.90	1.90 ^{hi}	1.90	1.94	1.92	1.90 ^{hi}	1.90	1.94	1.92	1.92 ^{fg}
T ₇	1.99	2.00	2.00	2.00 ^{hi}	2.01	2.02	2.02	2.02 ^{fg}	1.87	1.88	1.89	1.88 ^{ij}	1.89	1.90	1.91	1.88 ^{ij}	1.89	1.90	1.91	1.90 ^{gh}
T ₈	2.08	2.06	2.08	2.07 ^{bc}	2.11	2.08	2.10	2.10 ^b	1.96	1.94	1.96	1.95 ^{bc}	1.98	1.96	1.98	1.95 ^{bc}	1.98	1.96	1.98	1.97 ^{bc}
T ₉	2.03	2.02	2.02	2.02 ^{ef}	2.05	2.05	2.04	2.05 ^{de}	1.90	1.91	1.90	1.90 ^{gh}	1.92	1.93	1.92	1.90 ^{gh}	1.92	1.93	1.92	1.92 ^{ef}
T ₁₀	2.04	2.02	2.02	2.02 ^{ef}	2.06	2.04	2.04	2.05 ^{de}	1.88	1.90	1.91	1.90 ^{hi}	1.94	1.92	1.92	1.90 ^{hi}	1.94	1.92	1.92	1.93 ^{ef}
T ₁₁	2.02	2.02	2.02	2.02 ^{ef}	2.04	2.04	2.04	2.04 ^{de}	1.89	1.91	1.91	1.90 ^{ghi}	1.92	1.92	1.93	1.90 ^{ghi}	1.92	1.92	1.93	1.92 ^{ef}
T ₁₂	2.03	2.02	2.02	2.02 ^{ef}	2.05	2.05	2.04	2.05 ^{de}	1.91	1.91	1.91	1.91 ^{gh}	1.92	1.92	1.93	1.91 ^{gh}	1.92	1.92	1.93	1.92 ^{ef}
T ₁₃	1.99	2.00	2.00	2.00 ^{ghi}	2.02	2.02	2.02	2.02 ^{fg}	1.87	1.89	1.89	1.88 ^{ij}	1.89	1.90	1.91	1.88 ^{ij}	1.89	1.90	1.91	1.90 ^{gh}
T ₁₄	2.06	2.06	2.07	2.06 ^{bcd}	2.08	2.09	2.09	2.09 ^{bc}	1.93	1.95	1.95	1.94 ^{bcd}	1.95	1.96	1.97	1.94 ^{bcd}	1.95	1.96	1.97	1.96 ^{bcd}
T ₁₅	2.04	2.03	2.04	2.03 ^{ef}	2.06	2.05	2.06	2.06 ^{de}	1.92	1.91	1.92	1.92 ^{efgh}	1.93	1.93	1.94	1.92 ^{efgh}	1.93	1.93	1.94	1.93 ^{ef}
T ₁₆	2.05	2.04	2.04	2.04 ^{de}	2.07	2.06	2.07	2.07 ^{cd}	1.92	1.92	1.93	1.92 ^{def}	1.94	1.94	1.95	1.92 ^{def}	1.94	1.94	1.95	1.94 ^{de}
Mean (Y)	2.03 ^a	2.04 ^a	2.04 ^a		2.05 ^a	2.06 ^a	2.06 ^a		1.91 ^b	1.92 ^a	1.92 ^a		1.93 ^b	1.94 ^a	1.94 ^a		1.93 ^b	1.94 ^a	1.94 ^a	
Range	0.15					0.15					0.15					0.15				
T	LSD (P<0.05)					SEm ±					SE(d)					LSD (P<0.05)				
Y	0.005					0.002					0.002					0.003				
T*Y	0.002					0.001					0.001					0.001				
	0.008					0.003					0.003					0.006				

[Treatments (Spiked as concentration (ppm) in pots): T₀: 0, T₁: 1.5, T₂: 3.0, T₃: 4.5, T₄: 6.0, T₅: 7.5, T₆: 9.0, T₇: 10.5, T₈: 12.0, T₉: 13.5, T₁₀: 15.0, T₁₁: 16.5, T₁₂: 18.0, T₁₃: 19.5, T₁₄: 21.0, T₁₅: 22.5, T₁₆: 24.0]; numbers followed by different letters indicate significant differences at p < 0.05 (otherwise statistically at par); NS: non-significant (p > 0.05); (Y₀: No yellow gypsum application, Y₃₀: Yellow gypsum at 30 kg ha⁻¹, Y₆₀: Yellow gypsum at 60 kg ha⁻¹)

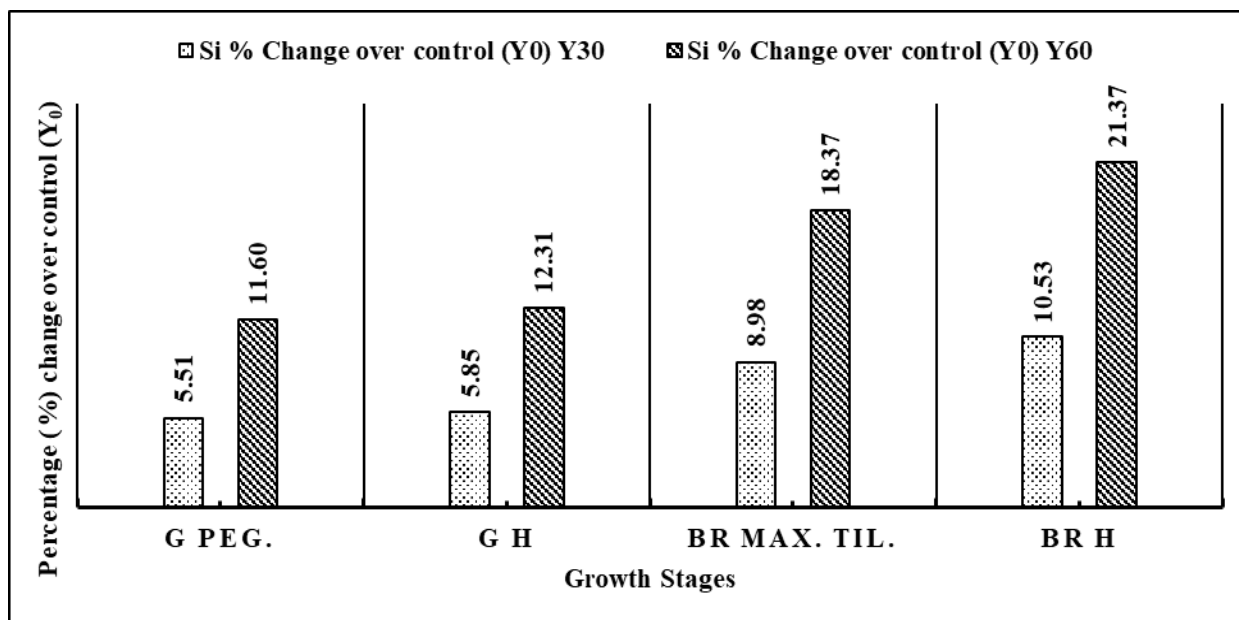


Fig. 3. Percent change in soil available silicon after application of yellow gypsum in groundnut and boro-rice crop. (Y₀: No yellow gypsum application; Y₃₀: Yellow gypsum at 30 kg ha⁻¹; Y₆₀: Yellow gypsum at 60 kg ha⁻¹)

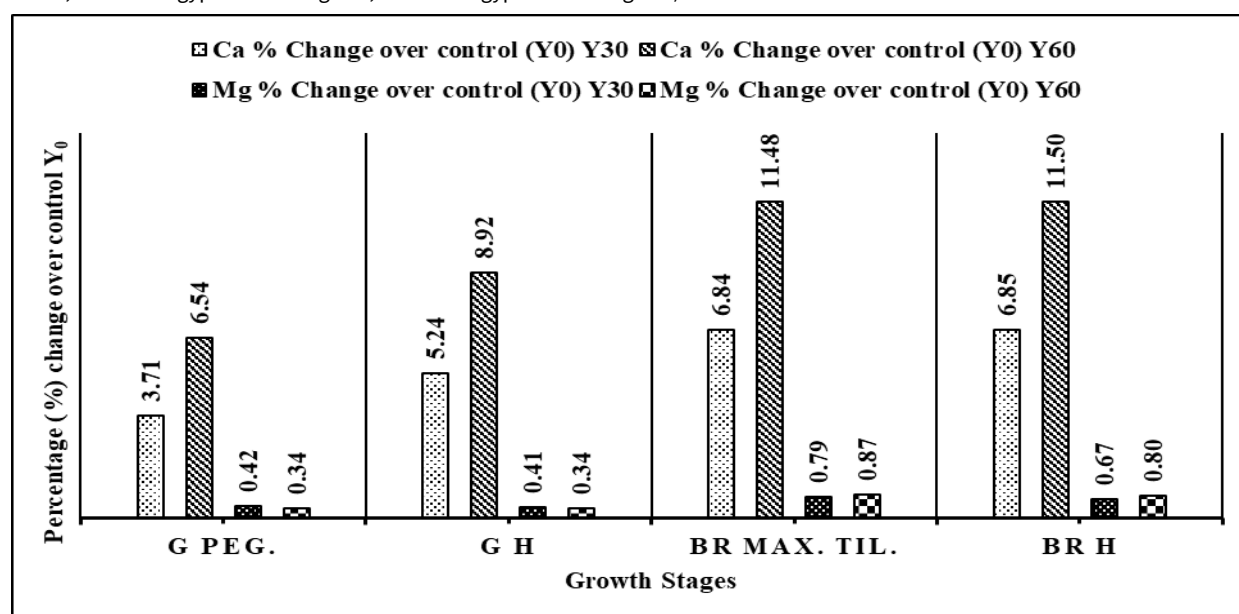


Fig. 4. Percent change in soil exchangeable calcium and magnesium after application of yellow gypsum in groundnut and boro-rice crop. (Y₀: No yellow gypsum application; Y₃₀: Yellow gypsum at 30 kg ha⁻¹; Y₆₀: Yellow gypsum at 60 kg ha⁻¹)

with Ca²⁺ ions to form sparingly soluble Ca₃(AsO₄)₂. The formation of such mineral phases reduces dissolved As concentrations and limits its mobility in soil solution. Previous studies have demonstrated that increasing Ca availability can promote the formation of stable AsO₄³⁻-bearing minerals, thereby decreasing As solubility and facilitating long-term immobilization in soils (36).

In the present study, the reduction in As availability following the application of YG can be explained by Ca mediated stabilization mechanisms. Gypsum serves as a readily soluble source of Ca²⁺, which enhances both precipitation and adsorption reactions in soil, thereby transforming labile As fractions into more stable, mineral-associated forms. This process reduces As mobility and bioavailability, thereby improving soil environmental quality. Similar observations have been reported in contaminated paddy soils, where gypsum-based amendments significantly decreased As bioavailability through stabilization processes (37).

In addition to adsorption and precipitation, Ca may facilitate the incorporation of As into secondary mineral phases, which further strengthens its long-term stabilization in soil systems

(54). The application of YG also increases the availability of exchangeable Ca²⁺ by enhancing soil base saturation and releasing Ca²⁺ during its dissolution, thereby improving the soil chemical environment (55, 56). The increased presence of Ca²⁺ not only supports As immobilization but also contributes to overall improvements in soil fertility. These findings are consistent with earlier reports which demonstrated that Ca-rich amendments such as gypsum effectively reduce As availability while improving soil properties (22, 53). Overall, the results confirm that the YG application promotes As stabilization through multiple Ca-driven mechanisms, making it a suitable amendment for managing As-contaminated soils.

Effect of yellow gypsum on soil available (DTPA extractable) iron and manganese

No significant ($p > 0.05$) effect of YG was observed on DTPA-extractable Fe and Mn across all the stages under different As treatments, except for a significant ($p < 0.05$) difference at kharif groundnut harvest. Diethylenetriaminepentaacetic acid-extractable Fe and Mn ranged from 46.04-49.70 and 20.01-20.57 mg kg⁻¹,

respectively, with the highest values in T_{16} (48.05 and 20.37 mg kg⁻¹) and the lowest in T_8 (47.72 and 20.21 mg kg⁻¹) (Tables 9 and 10). The decline in Fe and Mn indicated greater uptake by crops during growth.

Application of YG significantly increased available Fe with increasing dosage, while Mn showed only a slight improvement. The highest mean Fe (49.96–47.16 mg kg⁻¹) and Mn (20.88–16.63 mg kg⁻¹) were recorded under YG at 60 kg ha⁻¹ (Y_{60}), followed by Y_{30} , with the lowest in control (Y_0) (Tables 9 and 10). Compared to control, Y_{60} showed the highest Fe (6.25–15.34 %) and Mn (2.05 %) increases (Fig. 5).

The presence of Fe (Fe_2O_3 -5.04 %) and Mn (MnO-0.124 %) in the applied YG may be the reason for the increase in soil accessible (DTPA extractable) Fe and Mn in the treated treatments as compared to the control (Y_0). It was also reported that the application of YG increased the amount of DTPA-extractable Mn in both acidic and neutral soils used for maize cultivation (22). According to findings of another study, applying gypsum to wheat crops enhanced the micronutrient content, particularly Mn and Fe, in postharvest soils (57). Normally, gypsum application is thought to have little effect on the availability of micronutrients in soil.

Conclusion

The present study demonstrates that YG derived from LD-slag, a by-product of the steel industry, has considerable potential as an alternative soil amendment supplying essential nutrients such as Ca, S, Si, P, Fe and Mg. Application of YG resulted in a slight increase in soil pH and a significant improvement in soil OC content with increasing application rates. Furthermore, the availability of key nutrients, including Ca, S, Si, P, Fe and Mn, increased significantly ($p < 0.05$) in both kharif groundnut and boro-rice cropping systems. Among the evaluated treatments, the application of YG at 60 kg ha⁻¹ proved to be the most effective rate for improving nutrient availability in As-contaminated soils. These results indicate that YG can enhance soil fertility and nutrient dynamics, reduce the bioavailability of As in contaminated soil and simultaneously promote the productive utilization of industrial by-products in sustainable agricultural systems.

However, further research is required to validate these findings under field conditions. Multi-location trials across different soil types and agro-climatic regions are necessary to confirm the consistency and scalability of the observed effects. Long-term studies are also needed to assess the cumulative impacts of repeated YG application on soil health, nutrient cycling and the stability of As immobilization. Additionally, future research should evaluate crop productivity, As uptake and translocation in plant tissues and potential food safety implications to develop robust recommendations for the safe and sustainable use of YG in As-affected soils.

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Authors' contributions

KP carried out data curation and statistical analysis, wrote and reviewed and edited the manuscript and designed and investigated the work. PKP participated in the design and supervision of the work. SP participated in the review and editing of the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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Table 9. Effect of yellow gypsum on soil available (DTPA Extractable) Iron content under different arsenic concentration treatments at different stages of groundnut and boro-rice crop

Treatment	Groundnut												Boro-rice																	
	Pegging						Harvest						Maximum tillering						Harvest											
	Y ₀		Y ₃₀		Y ₆₀		Mean (T)		Y ₀		Y ₃₀		Y ₆₀		Mean (T)		Y ₀		Y ₃₀		Y ₆₀		Mean (T)		Y ₀		Y ₃₀		Y ₆₀	
	Y ₀	Y ₃₀	Y ₀	Y ₃₀	Y ₀	Y ₃₀	Mean (T)	Y ₀	Y ₃₀	Y ₀	Y ₃₀	Y ₀	Y ₃₀	Y ₀	Y ₃₀	Mean (T)	Y ₀	Y ₃₀	Y ₀	Y ₃₀	Y ₀	Y ₃₀	Y ₀	Y ₃₀	Y ₀	Y ₃₀	Y ₀	Y ₃₀	Y ₀	Y ₃₀
T ₀	47.14	48.58	50.04	48.58	46.31	47.96	49.64	47.97	43.64	46.64	49.64	46.64	40.96	44.07	47.19	44.07	44.07	47.19	44.07	44.07	44.07	44.07	44.07	44.07	44.07	44.07	44.07	44.07	44.07	44.07
T ₁	47.16	48.54	50.06	48.58	46.34	47.92	49.66	47.97	43.66	46.59	49.67	46.59	40.99	44.03	47.21	44.07	44.07	47.21	44.07	44.07	44.07	44.07	44.07	44.07	44.07	44.07	44.07	44.07	44.07	44.07
T ₂	47.07	48.54	49.95	48.52	46.25	47.92	49.55	47.91	43.57	46.59	49.55	46.57	40.90	44.03	47.10	44.01	44.01	47.10	44.01	44.01	44.01	44.01	44.01	44.01	44.01	44.01	44.01	44.01	44.01	44.01
T ₃	47.01	48.39	49.80	48.40	46.19	47.77	49.40	47.79	43.50	46.43	49.39	46.44	40.83	43.87	46.95	43.88	43.88	46.95	43.88	43.88	43.88	43.88	43.88	43.88	43.88	43.88	43.88	43.88	43.88	43.88
T ₄	47.01	48.48	49.93	48.47	46.19	47.86	49.53	47.86	43.50	46.52	49.53	46.52	40.83	43.96	47.08	43.96	43.96	47.08	43.96	43.96	43.96	43.96	43.96	43.96	43.96	43.96	43.96	43.96	43.96	43.96
T ₅	46.97	48.31	49.80	48.36	46.14	47.69	49.40	47.74	43.46	46.34	49.39	46.40	40.79	43.79	46.95	43.84	43.84	46.95	43.84	43.84	43.84	43.84	43.84	43.84	43.84	43.84	43.84	43.84	43.84	43.84
T ₆	46.86	48.43	49.93	48.41	46.04	47.82	49.53	47.79	43.35	46.48	49.53	46.45	40.68	43.92	47.08	43.89	43.89	47.08	43.89	43.89	43.89	43.89	43.89	43.89	43.89	43.89	43.89	43.89	43.89	43.89
T ₇	46.86	48.35	49.82	48.34	46.04	47.73	49.42	47.73	43.35	46.39	49.41	46.38	40.68	43.83	46.97	43.83	43.83	46.97	43.83	43.83	43.83	43.83	43.83	43.83	43.83	43.83	43.83	43.83	43.83	43.83
T ₈	46.88	48.33	49.80	48.34	46.06	47.71	49.40	47.72	43.37	46.37	49.39	46.37	40.70	43.81	46.95	43.82	43.82	46.95	43.82	43.82	43.82	43.82	43.82	43.82	43.82	43.82	43.82	43.82	43.82	43.82
T ₉	46.94	48.43	49.97	48.44	46.12	47.81	49.56	47.83	43.51	46.56	49.65	46.58	40.84	44.00	47.20	44.01	44.01	47.20	44.01	44.01	44.01	44.01	44.01	44.01	44.01	44.01	44.01	44.01	44.01	44.01
T ₁₀	46.98	48.47	50.09	48.51	46.16	47.85	49.70	47.90	43.56	46.60	49.79	46.65	40.89	44.04	47.33	44.09	44.09	47.33	44.09	44.09	44.09	44.09	44.09	44.09	44.09	44.09	44.09	44.09	44.09	44.09
T ₁₁	46.94	48.47	50.01	48.47	46.12	47.85	49.61	47.86	43.51	46.60	49.70	46.61	40.84	44.04	47.25	44.04	44.04	47.25	44.04	44.04	44.04	44.04	44.04	44.04	44.04	44.04	44.04	44.04	44.04	44.04
T ₁₂	47.17	48.68	50.05	48.63	46.35	48.06	49.65	48.02	43.77	46.83	49.75	46.78	41.09	44.26	47.29	44.21	44.21	47.29	44.21	44.21	44.21	44.21	44.21	44.21	44.21	44.21	44.21	44.21	44.21	44.21
T ₁₃	47.04	48.47	50.05	48.52	46.22	47.85	49.65	47.91	43.63	46.60	49.75	46.66	40.95	44.04	47.29	44.09	44.09	47.29	44.09	44.09	44.09	44.09	44.09	44.09	44.09	44.09	44.09	44.09	44.09	44.09
T ₁₄	47.09	48.53	50.01	48.54	46.26	47.91	49.61	47.93	43.68	46.67	49.70	46.68	41.00	44.11	47.25	44.12	44.12	47.25	44.12	44.12	44.12	44.12	44.12	44.12	44.12	44.12	44.12	44.12	44.12	44.12
T ₁₅	47.07	48.47	50.01	48.51	46.24	47.85	49.61	47.90	43.65	46.60	49.70	46.65	40.97	44.04	47.25	44.09	44.09	47.25	44.09	44.09	44.09	44.09	44.09	44.09	44.09	44.09	44.09	44.09	44.09	44.09
T ₁₆	47.21	48.68	50.09	48.66	46.39	48.06	49.70	48.05	43.81	46.83	49.79	46.81	41.13	44.26	47.33	44.24	44.24	47.33	44.24	44.24	44.24	44.24	44.24	44.24	44.24	44.24	44.24	44.24	44.24	44.24
Mean (Y)	47.02 ^c	48.48 ^b	49.96 ^a		46.20 ^c	47.86 ^b	49.57 ^a		43.56 ^c	46.57 ^b	49.61 ^a		40.88 ^c	44.00 ^b	47.16 ^a			44.00 ^b	47.16 ^a											
Range		3.23				3.66				6.45				6.66				6.66												
T	LSD (<i>P</i> <0.05)						SEm ±	SE(d)	LSD (<i>P</i> <0.05)						SEm ±	SE(d)	LSD (<i>P</i> <0.05)						SEm ±	SE(d)						
T	NS						0.11	0.15	0.24						0.09	0.12	NS						0.12	0.17						
Y	0.12						0.04	0.06	0.10						0.04	0.05	0.14						0.05	0.07						
T*Y	NS						0.18	0.26	NS						0.15	0.22	NS						0.20	0.29						

[Treatments (Spiked as concentration (ppm) in pots): T₀: 0, T₁: 1.5, T₂: 3.0, T₃: 4.5, T₄: 6.0, T₅: 7.5, T₆: 9.0, T₇: 10.5, T₈: 12.0, T₉: 13.5, T₁₀: 15.0, T₁₁: 16.5, T₁₂: 18.0, T₁₃: 19.5, T₁₄: 21.0, T₁₅: 22.5, T₁₆: 24.0]; numbers followed by different letters indicate significant differences at $p < 0.05$ (otherwise statistically at par); NS: non-significant ($p > 0.05$); (Y₀- No yellow gypsum application, Y₃₀- Yellow gypsum at 30 kg ha⁻¹, Y₆₀- Yellow gypsum at 60 kg ha⁻¹)

Table 10. Effect of yellow gypsum on soil available (DTPA Extractable) manganese content under different arsenic concentration treatments at different stages of groundnut and boro-rice crop

Treatment	Groundnut						Boro-rice					
	Pegging			Harvest			Maximum Tillering			Harvest		
	Y ₀	Y ₃₀	Y ₆₀	Mean (T)	Y ₀	Y ₃₀	Y ₆₀	Mean (T)	Y ₀	Y ₃₀	Y ₆₀	Mean (T)
T ₀	20.49	20.68	20.89	20.69	20.11	20.31	20.52	20.31	18.16	18.33	18.52	18.34
T ₁	20.50	20.66	20.90	20.69	20.13	20.29	20.52	20.31	18.17	18.31	18.53	18.34
T ₂	20.47	20.66	20.86	20.66	20.09	20.29	20.48	20.29	18.14	18.31	18.49	18.31
T ₃	20.44	20.60	20.80	20.61	20.07	20.23	20.42	20.24	18.12	18.26	18.44	18.27
T ₄	20.44	20.64	20.85	20.64	20.07	20.26	20.47	20.27	18.12	18.29	18.48	18.30
T ₅	20.42	20.57	20.80	20.59	20.05	20.19	20.42	20.22	18.10	18.23	18.44	18.26
T ₆	20.38	20.62	20.85	20.61	20.01	20.25	20.47	20.24	18.07	18.28	18.48	18.27
T ₇	20.38	20.58	20.81	20.59	20.01	20.21	20.43	20.22	18.07	18.25	18.44	18.25
T ₈	20.39	20.58	20.80	20.59	20.02	20.20	20.42	20.21	18.07	18.24	18.44	18.25
T ₉	20.44	20.65	20.90	20.66	20.07	20.27	20.52	20.29	18.12	18.30	18.53	18.32
T ₁₀	20.46	20.66	20.95	20.69	20.09	20.29	20.57	20.32	18.14	18.32	18.57	18.34
T ₁₁	20.44	20.66	20.91	20.67	20.07	20.29	20.53	20.30	18.12	18.32	18.54	18.33
T ₁₂	20.54	20.75	20.93	20.74	20.17	20.38	20.55	20.36	18.21	18.39	18.55	18.38
T ₁₃	20.49	20.66	20.93	20.69	20.12	20.29	20.55	20.32	18.16	18.32	18.55	18.34
T ₁₄	20.50	20.69	20.91	20.70	20.13	20.32	20.53	20.33	18.18	18.34	18.54	18.35
T ₁₅	20.49	20.66	20.91	20.69	20.12	20.29	20.53	20.32	18.17	18.32	18.54	18.34
T ₁₆	20.56	20.75	20.95	20.75	20.18	20.38	20.57	20.37	18.22	18.39	18.57	18.39
Mean (Y)	20.46 ^c	20.65 ^b	20.88 ^a		20.09 ^c	20.28 ^b	20.50 ^a		18.14 ^c	18.31 ^b	18.51 ^a	
Range		3.23				0.56				0.50		
	LSD (P<0.05)	SEm ±	SE(d)		LSD (P<0.05)	SEm ±	SE(d)		LSD (P<0.05)	SEm ±	SE(d)	
T	NS	0.05	0.06		0.11	0.04	0.05		NS	0.05	0.069	
Y	0.05	0.02	0.03		0.04	0.02	0.02		0.06	0.02	0.029	
T*Y	NS	0.08	0.11		NS	0.06	0.09		NS	0.09	0.12	

[Treatments (Spiked as concentration (ppm) in pots]: T₀: 0, T₁: 1.5, T₂: 3.0, T₃: 4.5, T₄: 6.0, T₅: 7.5, T₆: 9.0, T₇: 10.5, T₈: 12.0, T₉: 13.5, T₁₀: 15.0, T₁₁: 16.5, T₁₂: 18.0, T₁₃: 19.5, T₁₄: 21.0, T₁₅: 22.5, T₁₆: 24.0]; numbers followed by different letters indicate significant differences at p < 0.05 (otherwise statistically at par); NS: non-significant (p > 0.05); (Y₀- No yellow gypsum application, Y₃₀: Yellow gypsum at 30 kg ha⁻¹, Y₆₀: Yellow gypsum at 60 kg ha⁻¹)

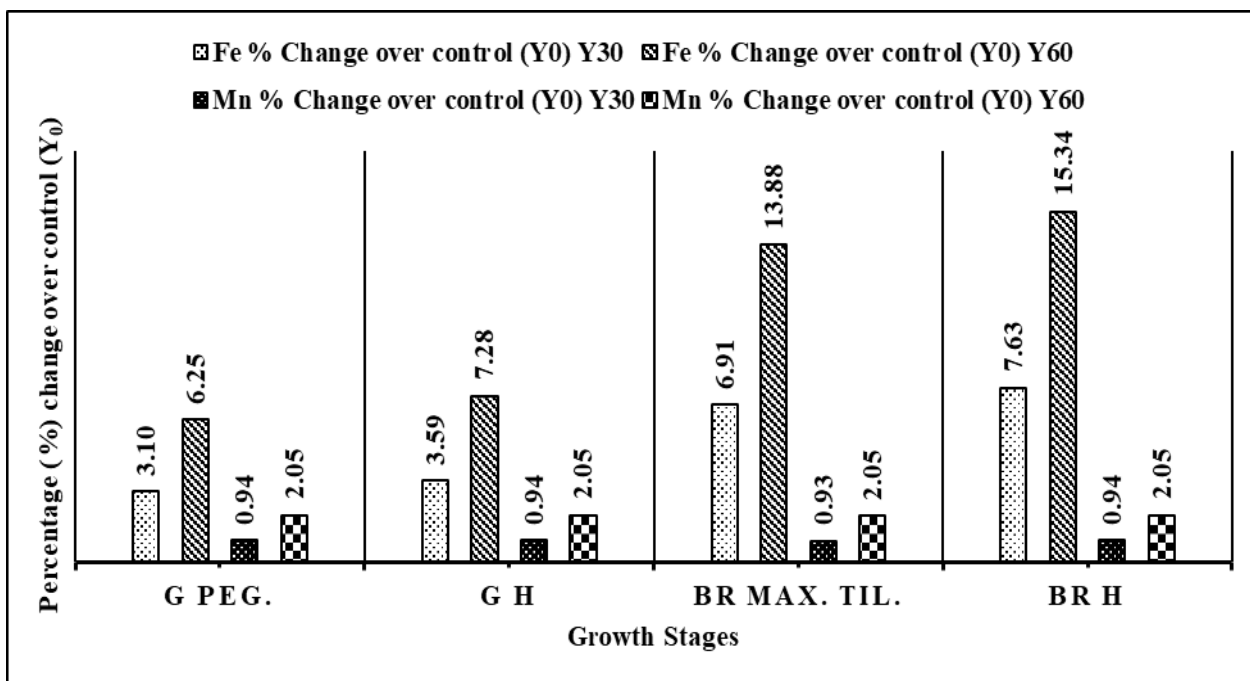


Fig. 5. Percent change in soil available (DTPA extractable) iron and manganese after application of yellow gypsum in groundnut and boro-rice crop. (Y₀: No yellow gypsum application; Y₃₀: Yellow gypsum at 30 kg ha⁻¹; Y₆₀: Yellow gypsum at 60 kg ha⁻¹)

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