

Regulatory effects of phosphogypsum application on soil quality and plant physiology: A global meta-analysis

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Abstract

Phosphogypsum (PG), a bulk solid by-product produced from wet phosphoric acid manufacturing, can be used as a soil amendment after harmless and functional modification in agricultural production. This greatly reduces the environmental and land pressure stemming from PG stockpiles but also conforms to the development of resource recycling and green agriculture. However, how PG application methods (alone or combined) and dosage gradients affect soil physicochemical properties, plant physiology, and microbial community structure has not been systematically or quantitatively assessed, limiting its precise and standardized use across diverse ecological regions and farming systems. Based on a strict screening of 44 global empirical studies, we conducted a multi-dimensional meta-analysis to systematically quantify the effects of PG application on soil quality, crop growth, enzyme activity, and soil microbial diversity. The results showed that the application of PG alone significantly improved soil fertility by increasing soil organic matter (+27.5%), field water holding capacity (+38.0%), available phosphorus (+58.6%), alkali-hydrolysable nitrogen (+25.0%) and ammonium nitrogen (+26.0%), total potassium (+15.8%) and total nitrogen (+21.3%), while reducing soil pH by 12%. At the plant level, PG significantly promoted biomass accumulation (+22.9%), plant height growth (+18.9%), root length (+16.5%), and calcium enrichment in the aboveground (+126.1%). In terms of combined application, the use of PG in conjunction with biochar reversed the acidification, increasing soil pH by 14.9%. The combined application of PG and compound fertilizer showed significant synergistic effects: soil total potassium content increased by 86.5%, K^+ and Ca^{2+} concentrations in plants increased by 112.3% and 147.9% respectively, Na^+ content significantly decreased by 85.7%, and simultaneously achieved a significant increase in crop yield (+43.2%) and plant height (+35.3%). At the biological response level, PG significantly enhanced soil β -glucosidase (+6.6%) and urease (+20.4%) activities and increased chlorophyll content in plants (+20.3%). Meanwhile, it significantly activated the plant antioxidant system, with superoxide dismutase (SOD) and catalase (CAT) activities increasing by 15.6% and 42.6% respectively. However, a decrease of 18.2% in fungal community α -diversity (Chao1 index) was observed, suggesting the need to pay attention to the potential regulatory effects of long-term application on the structure of the soil microbial community. The sensitivity analysis of application dosage showed that the medium and low dosage range of 10%–50% (mass ratio) of PG application presented the best comprehensive benefits in most studies, which is conducive to expanding the soil nutrient pool and promoting the stable growth of crops. In conclusion, this study provides systematic scientific basis and practical parameter support for the agricultural resource utilization of phosphogypsum under the premise of ecological safety, and has important theoretical value and application significance for building a modern farmland ecosystem that is nutrient-efficient, environmentally friendly, and resiliently sustainable.

Highlights

- Soil and plant responses to phosphogypsum addition were systematically evaluated.

- Effects of single and combined application of phosphogypsum and the application rates were quantitatively summarized.
- Phosphogypsum promotes plant growth by improving soil properties and enhancing antioxidant defense capabilities.
- Application of phosphogypsum at medium-to-low rates (10–50% by mass) yielded the greatest overall agronomic and environmental benefits.

Introduction

Phosphogypsum (PG) is the primary byproduct of wet-process phosphoric acid and phosphate fertilizer production (Wang et al., 2026), and also one of the largest solid waste in the chemical industry (approximately 4.5–5.0 tons of phosphogypsum are generated per 1.0 ton of phosphoric acid produced) (Qian et al., 2024). The primary component is calcium sulfate dihydrate ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), accompanied by impurities such as free acid, phosphates, fluorides, trace heavy metals, and radionuclides (Pérez-López et al., 2011). Large-scale storage of phosphogypsum not only occupies substantial land resources but also poses potential environmental risks to surrounding water bodies, soils, and ecosystems (Wang et al., 2024). However, its rich content of plant-essential nutrients like calcium and sulfur demonstrates significant potential for agricultural soil improvement (Du et al., 2025; Yamani et al., 2026). In response to the environmental issues caused by the large-scale stockpiling of phosphogypsum, various treatment methods have been developed. Modifying phosphogypsum through physicochemical methods such as leaching and lime neutralization can effectively achieve its harmless treatment and resource recovery (Costa et al., 2025). In addition, thermochemical treatment technologies have garnered significant attention, primarily including calcination, co-pyrolysis, and reduction pyrolysis. The objective of these methods is to improve processing techniques and recover resources, thereby achieving high-value utilization of phosphogypsum (Zhao et al., 2026). Safe utilization could alleviate environmental pressures from stockpiling while substituting natural gypsum for agricultural soil improvement, establishing a circular economy model of “treating waste with waste”. Extensive literature indicates that phosphogypsum application positively improves soil physicochemical fertility and promotes plant growth (Shruthi et al., 2024). In saline-alkali soil remediation, the calcium ions in phosphogypsum can replace sodium ions on soil colloids, effectively reducing soil alkalinity and pH while improving soil structure (Guo et al., 2025). Phosphogypsum application significantly ($P < 0.05$) enhanced carbon, nitrogen, and phosphorus use efficiency in saline-alkali paddy fields (Lu et al., 2023). Regarding acidic soil remediation, phosphogypsum application significantly reduced exchangeable aluminum content and aluminum saturation through calcium-aluminum ion exchange, increased soil calcium concentration and activity, partially elevated total exchangeable base cations, and promoted soil pH transition from acidic to slightly acidic (Bouray et al., 2022). Li et al. (2023) further demonstrated that phosphogypsum application had beneficial effects on enzyme activity and microbial diversity by altering soil physicochemical properties, potentially enriching salt-tolerant microbial communities, and promoting plant growth by improving the root zone environment (El-Shamy et al., 2022). However, current research is mostly confined to specific soil types (such as saline-alkali soil or acidic soil), particular crop species

or specific geographical regions. A systematic assessment framework covering soil properties and plant growth has yet to be established, and there is a particular lack of in-depth analysis of the entire process of soil nutrient transformation and absorption and utilization. Therefore, this study aims to integrate existing fragmented evidence through meta-analysis and systematically summarize the overall impact patterns of phosphogypsum on soil physicochemical fertility and plant growth.

The synergistic effects of phosphogypsum have been demonstrated with several materials such as biochar, organic fertilizers, and red mud (Bana et al., 2015; de Souza Costa et al., 2021; Elbagory et al., 2024). For instance, Palencia et al. (2024) found that co-application of phosphogypsum and red mud overcomes high-dose toxicity while converting it into plant-available phosphorus, calcium, and magnesium sources. Mu et al. (2024) demonstrated that phosphogypsum combined with biochar effectively remediates cadmium-contaminated soil and promotes Chinese cabbage growth. Through synergistic effects, this approach significantly elevates soil pH and nutrient levels while minimizing available cadmium, thereby efficiently blocking cadmium transfer to Chinese cabbage. For instance, a two-year field trial with varying phosphogypsum application gradients was conducted to systematically evaluate its comprehensive effects on crop yield, soil structure, and nutrient utilization (Outbakat et al., 2024), and it determined that 3 t/ha was the optimal phosphogypsum application rate. At this rate, phosphogypsum effectively promoted soil aggregate formation by supplementing Ca^{2+} and SO_4^{2-} , while optimizing crop uptake of nutrients like nitrogen and calcium, resulting in a 37% increase in crop biomass. In contrast, a greenhouse pot experiment with four phosphogypsum rates (0, 1, 3, and 9 t/ha) combined with lime application demonstrated that the treatment of 9 t/ha phosphogypsum plus 2 t/ha lime most significantly enhanced soil phosphorus availability and phosphorus and sulfur uptake by alfalfa, while also producing the highest alfalfa biomass (Bouray et al., 2020). The inconsistency of these results indicates that summarizing and integrating the information on the responses of soil and plants to phosphogypsum application will be helpful for its engineering application in agricultural production and ecological restoration.

Therefore, this study systematically evaluated the effects of application of phosphogypsum alone and combined application of phosphogypsum with other substances on soil fertility and plant growth. The objectives were: (i) to determine the responses of soil physicochemical fertility and plant morphological and physiological characteristics to phosphogypsum addition; (ii) to compare the effects of combined application of phosphogypsum with different materials and their influencing indicators; and (iii) to clarify the pathways and mechanisms by which the application rate of phosphogypsum affects soil fertility and plant growth.

Materials and Methods

- Data collection

This study utilized Chinese and English databases including CNKI (<https://www.cnki.net/>), Web of Science (<http://apps.webofknowledge.com>), and X-MOL (<https://www.x-mol.com>). Various keyword

combinations, including (“phosphogypsum”) and (“soil” or “soil microorganism” or “plant” or “crop”), were used to retrieve articles published up to August 2025 concerning soil and plant changes following phosphogypsum application. After initial screening based on titles and abstracts, full texts were carefully reviewed for further selection. Data were extracted and organized from the dataset according to the following criteria: (1) Experimental design must include a control without phosphogypsum application and a treatment with phosphogypsum application, with all other conditions held constant; (2) The number of replicates, mean, standard deviation, or standard error for each parameter must be explicitly stated in the article or extractable via Web Plot Digitizer; (3) Each treatment should have at least three replicate experiments. Based on these criteria, 44 valid articles were selected (**Fig. S1**).

From the selected studies, we recorded soil type, experimental design, primary phosphogypsum components, phosphogypsum composite material type, crop type, and phosphogypsum application rate as the key parameters. The following response variables were considered: 1) Soil physical properties: soil moisture content (SMC), bulk density (BD); 2) Soil chemical properties: pH, soil electrical conductivity (EC); 3) Soil nutrient indicators: soil organic matter (SOM), available nitrogen (AN), available phosphorus (AP), available potassium (AK), total nitrogen (TN), total phosphorus (TP), total potassium (TK), ammonium nitrogen (NH₄⁺-N), nitrate nitrogen (NO₃⁻-N); 4) Soil biological properties: β-glucosidase activity (β-Glu), urease activity (Urease), alkaline phosphatase activity (ALP), acid phosphatase activity (ACP), bacterial shannon index (Shannon), bacterial chao1 index (Chao1), fungal shannon index (Shannon-F), fungal chao1 index (Chao1-F); 5) Plant growth indicators: crop yield (Yield), aboveground biomass (Biomass), plant height, root length; 6) Plant nutrient indicators: plant total nitrogen (Plant TN), plant total phosphorus (Plant TP), plant total potassium (Plant TK), potassium ion concentration (K⁺), calcium ion concentration (Ca²⁺), sodium ion concentration (Na⁺); 7) Plant physiological indicators: chlorophyll content (Chl), superoxide dismutase activity (SOD), catalase activity (CAT). Additionally, the above information is categorized as follows: 1) Phosphogypsum composite material types are categorized as: phosphogypsum application alone, phosphogypsum combined with biochar, phosphogypsum combined with biochar and lime, phosphogypsum combined with compound fertilizer, phosphogypsum combined with farmyard manure, phosphogypsum combined with farmyard manure and wood peat, phosphogypsum combined with red mud, phosphogypsum combined with biochar and compound fertilizer, phosphogypsum combined with furfural residue; 2) Phosphogypsum application rates are categorized as < 1%, 1%–5%, 5%–10%, 10%–50%, 50%–100%.

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Data directly provided in the literature or presented in graphical form were collected using Web Plot Digitizer 4.8 (Pacifica, California, USA). When standard errors were reported in articles, they were converted to standard deviations using the following formula:

$$SD = SE \times \sqrt{N}$$

Where SD is the standard deviation; SE is the standard error; N is the sample size.

The impact of phosphogypsum on different variables (X) was assessed using the natural log-transformed response ratio (RR) (i.e., the effect size). The formula is as follows:

$$RR = X_t / X_c = \ln X_t - \ln X_c$$

In this formula, RR stands for the effect size of the research target variable, X_t denotes the average value of every parameter within the treatment group, while X_c stands for the average value of each parameter in the control group.

The variance (V) of each RR was calculated as follows:

$$V = \frac{S_t^2}{N_t X_t^2} + \frac{S_c^2}{N_c X_c^2}$$

Where S_t , S_c , N_t , N_c , X_t , and X_c represent the standard deviation, sample size, and mean value for the treatment group and control group, respectively.

Additionally, the cumulative effect value is converted to a percentage change to interpret the impact of phosphogypsum addition on soil fertility and plant growth. The formula is as follows:

$$\text{Change } [\%] = [\exp(\ln RR) - 1] \times 100$$

Meta-analysis was performed using the “rma” function in the “metafor” package of R version 4.5.1. The analysis comprised two steps: random-effects model analysis and mixed-effects model analysis. First, a random-effects model was applied to assess the magnitude of effect sizes and 95% confidence intervals (CI) for each indicator between the phosphogypsum-treated and untreated groups. If the CI for the mean effect size did not overlap with zero, this was considered indicative of a significant difference. For these analyses, we assessed heterogeneity using Cochran’s Q-test (QT), which examines whether the observed variability in effect sizes or outcomes exceeds what would be expected from sampling variation alone. After assessing heterogeneity, the random-effects meta-analysis revealed significant residual heterogeneity (**Tables S1-S2**). Therefore, a mixed-effects model (Step 2) was employed to examine the relationship between the independent variable and the outcome variable (categorical or continuous).

Egger's test was employed to assess publication bias. Rosenberg's failure-safe number (Nfs) was calculated to evaluate the robustness of our results to publication bias. Even in the presence of publication bias ($P < 0.05$), results were considered reliable if $Nfs > 5k + 10$ (k = sample size) (**Table S3**).

Results

- Responses of soil enzyme activity, nitrogen content, microbial diversity and plant nutrients to the addition of phosphogypsum alone

Compared with the control without phosphogypsum application, the application of phosphogypsum alone significantly increased soil β -glucosidase activity (β -Glu) and urease activity (Urease) by 6.6% and 20.4% respectively, while the alkaline phosphatase activity (ALP) decreased by 5.9% (Fig. 1a). Soil ammonium nitrogen and nitrate nitrogen also showed differentiated responses to phosphogypsum addition. The content of ammonium nitrogen ($\text{NH}_4^+\text{-N}$) significantly increased by 26.0%, while the content of nitrate nitrogen ($\text{NO}_3^-\text{-N}$) significantly decreased by 86.7% (Fig. 1b). Notably, in terms of the negative effects of phosphogypsum, it significantly reduced fungal diversity, as indicated by the Chao1 index, by 18.2% (Fig. 1c). The impact of phosphogypsum on plants was generally positive, with its application significantly increasing plant catalase activity (CAT), total nitrogen (Plant TN), total phosphorus (Plant TP), and total potassium (Plant TK) contents by 42.6%, 89.3%, 57.5%, and 25.5% respectively (Fig. 1d, e).

Error bars indicate 95% confidence intervals (CI). Numbers in parentheses denote sample sizes for each variable. * Indicates significant differences compared with the control (without phosphogypsum application): * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

- Influence of different combinations of phosphogypsum on soil fertility

The average percentage changes in soil nutrients and physicochemical properties under different phosphogypsum combinations as well as their 95% confidence intervals are shown in Fig. 2. The application of phosphogypsum alone, as well as phosphogypsum combined with farmyard manure and wood peat, significantly reduced pH by 12.6% ($P < 0.001$) and 9.4% ($P < 0.01$), respectively, while co-application with biochar significantly increased pH by 14.9% ($P < 0.001$). Soil electrical conductivity (EC) increased significantly ($P < 0.001$) by 83.1% under the application of phosphogypsum-red mud composite, with upward trends also observed under phosphogypsum alone and composite treatments with farmyard manure and wood peat, showing increases of 7.1% and 38.4%, respectively. Application of phosphogypsum alone significantly ($P < 0.001$) increased soil organic matter (SOM) by 27.5%, while the combined application of biochar was superior to phosphogypsum application alone, significantly ($P < 0.001$) increasing SOM by 59.4%. Additionally, phosphogypsum alone significantly ($P < 0.05$) increased soil moisture content (SMC) by 38.0%. Regarding soil nutrients, the application of phosphogypsum alone significantly ($P < 0.001$) increased available phosphorus (AP) by 58.6%, alkali-hydrolyzable nitrogen (AN) by 25.0%, total potassium (TK) by 15.8%, and total nitrogen (TN) by 21.3%. Phosphogypsum combined with biochar significantly ($P < 0.001$) increased available potassium (AK) content by 63.6%. Phosphogypsum combined with compound fertilizer significantly ($P < 0.05$) increased total potassium (TK) by 86.5%. Phosphogypsum combined with farmyard manure significantly ($P < 0.05$) increased total nitrogen (TN) by 26.4%.

Error bars indicate 95% confidence intervals (CI); Numbers in parentheses denote sample sizes for each variable. * Indicates significant differences compared to the control (without phosphogypsum application): * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

- Plant responses to phosphogypsum amendment

Based on the above-mentioned influence of phosphogypsum on soil properties, we further analyzed the plant growth effects brought by the changes in soil nutrients. Figure 3 shows the responses of plant growth, nutrient and physiological indicators under different phosphogypsum composites. Phosphogypsum-modified compound fertilizer and phosphogypsum-modified manure significantly increased crop yield by 43.2% and 34.9%, respectively. Similarly, the application of phosphogypsum alone and the combination of phosphogypsum and biochar significantly increased plant biomass by 22.9% and 151.0%, and root length by 16.5% and 23.6%, respectively. Plant height was more sensitive to phosphogypsum, and both the application of phosphogypsum alone and its combined application significantly increased plant height by 18.9%–68.6%. In terms of plant nutrition, the application of phosphogypsum alone increased the calcium ion (Ca^{2+}) content of plants by 126.1%, and the application of phosphogypsum with compound fertilizer significantly increased the potassium ion (K^+) and calcium ion (Ca^{2+}) contents by 112.3% and 147.9%, respectively, but significantly decreased the sodium ion (Na^+) content by 85.7%. This inhibitory effect was reversed when red mud was added, and Na^+ content increased by 139.4%. At the plant physiological level, the application of phosphogypsum alone significantly increased chlorophyll content (Chl) and superoxide dismutase activity (SOD) by 20.3% and 15.6%, respectively. Similarly, the combined application of phosphogypsum and furfural residue (PG + FR) also increased SOD activity by 15.2%.

- Effects of phosphogypsum application rates on soil fertility and plant growth

The effect sizes and their 95% confidence intervals for phosphogypsum application rates on soil physicochemical properties and nutrients are shown in Fig. 4. The results showed soil pH decreased with the increasing rates of PG application. When the application rates of PG were 10%–50%, the pH value significantly ($P < 0.01$) decreased by 10.7%, and as the application rate of PG increased to 50%–100%, the rate of pH value decrease reached 24.3% (Fig. 4a). The increase of PG aggravated the soil bulk density. As the PG content increased from 1%–5% to 5%–10%, the soil bulk density (BD) increased by 9.7% (Fig. 4b). Although the addition of PG was beneficial to soil water retention, it was not the case that the higher the application rate, the better the water retention. When the application rates of PG were 10%–50%, the increase in soil moisture content was the largest, reaching 124.8%. However, as the application rate increased to 50%–100%, the increase in soil moisture content dropped to 42.4% (Fig. 4c). In terms of soil nutrients, total nitrogen (TN), available phosphorus (AP), and available potassium (AK) were not sensitive to the application rate of PG (Fig. 4d, f, g). Soil total phosphorus (TP) showed an increasing trend at medium and low application rates, but when the PG content increased to 50%–100%, TP significantly decreased by 87.3% (Fig. 4e). Soil organic matter (SOM), as the most important indicator of soil fertility, significantly increased when the PG addition rate was higher than 5%, and at the application rate of 10%–50%, the increase in SOM reached the highest, which was 50.8% (Fig. 4h).

If the CI does not overlap with the 0 line, the effect is significant ($P < 0.05$). * indicates a significant effect of phosphogypsum application ($P < 0.05$), ** indicates a significant effect ($P < 0.01$), and *** indicates a highly significant effect ($P < 0.001$).

The application rates of low to medium phosphogypsum (PG) were beneficial to plant growth, as indicated by the increase in plant height and root length. The addition of 1%-5% PG increased plant height and root length by 36.5% and 22.1%, respectively (Fig. 5a, b). Similarly, the addition of medium rates of PG (10%–50%) increased plant biomass by 40.1%. However, this positive effect was reversed at high doses of PG, with the application of 50%–100% PG reducing plant biomass by 20.7% (Fig. 5c). Crop yield was not significantly affected by the application rate of PG (Fig. 5d). The above-mentioned growth-promoting effects were accompanied by changes in enzyme activity and chlorophyll content. Catalase (CAT) activity significantly increased by 40.3% at lower PG application rates (Fig. 5e), while chlorophyll content significantly increased by 22.7% at medium PG application rates (Fig. 5f).

If the CI does not overlap with the 0 line, the effect is significant ($P < 0.05$); * indicates a significant effect of phosphogypsum application ($P < 0.05$); ** indicates a significant effect of phosphogypsum application ($P < 0.01$); *** indicates a highly significant effect of phosphogypsum application ($P < 0.001$).

- Correlation analysis of phosphogypsum application rate with soil physiochemical properties and plant growth

Correlation analysis indicated that the application rate of phosphogypsum was significantly negatively correlated with soil pH and plant height, while it was significantly positively correlated with soil organic matter (SOM) (**Fig. 6A, B, C**). However, no significant correlations were found between the application rate of phosphogypsum and other soil and plant indicators (**Fig. S2**). According to the structural equation model (SEM), phosphogypsum application exerted stronger direct effects on SOM accumulation than indirect effects mediated by soil pH and plant-related variables. Changes in soil pH and plant growth indicators driven by phosphogypsum addition explained 57–6 % of SOM variation, 6 % of soil pH variation and 3 % of plant height variation (**Fig. 6D, E**).

Figure 6 Relationship between phosphogypsum application rate and soil pH, organic matter, and plant height. LnRR denotes the natural logarithm of the response ratio between phosphogypsum-treated and control groups (A-C). SEM reveals the effect of phosphogypsum application rate on SOM through response ratios (LnRR) of soil pH, total phosphorus, plant height, and biomass. Arrows indicate the direction of hypothesized causal relationships. Positive correlations are indicated by green arrows, negative correlations by orange arrows, and dashed arrows denote non-significant correlations. Numbers on arrows represent normalization factors, and R^2 indicates the percentage of variance explained. * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$ (D, E).

Discussion

- Effects of phosphogypsum on soil physicochemical properties

Phosphogypsum optimizes soil physicochemical properties through multiple mechanisms including chemical neutralization, ion exchange, and structural improvement, thereby creating a more suitable rhizosphere environment for plant growth (Umair et al., 2026). As a core indicator of soil fertility, pH

determines the forms and availability of nutrient elements and regulates enzyme activity, microbial community structure, and root tolerance thresholds for metal toxicity (Qin et al., 2024). Our results showed that application of phosphogypsum alone significantly ($P < 0.001$) lowered soil pH (Fig. 2). This effect likely stems from residual sulfates and soluble acidic impurities (pH 2.0–4.9) in phosphogypsum. Upon incorporation, free H^+ rapidly neutralizes OH^- , CO_3^{2-} , and HCO_3^- in saline-alkali soils (Al-Enazy et al., 2018). Concurrently, Ca^{2+} from calcium sulfate dihydrate ($CaSO_4 \cdot 2H_2O$) displaced H^+ adsorbed on soil colloidal surfaces, thereby increasing the activity of H^+ in solution and further lowering pH (Smaoui-Jardak et al., 2024). Moreover, Ca^{2+} reacts with HCO_3^- and CO_3^{2-} in the soil solution to form $CaCO_3$ and $Ca(HCO_3)_2$ precipitates or immobilize carbonate ions, lowering the pH of saline-alkali soils (Al-Enazy et al., 2018). Furthermore, our study revealed that soil pH decreased with increasing PG application rates (Fig. 4), indicating that higher phosphogypsum application effectively improves saline-alkali soil structure. The current finding is consistent with previous results showing a decreasing soil pH trend with increasing phosphogypsum application; for instance, Hasana et al. (2022) demonstrated that increasing the application rates from 0% to 200% reduced soil pH from 9.39 to 7.39. The mixture of phosphogypsum and biochar reversed the acidifying effect of phosphogypsum and elevated soil pH as compared to applying phosphogypsum alone. This effect may be attributed to the fact that biochar is rich in alkaline ash components such as carbonates. When applied to soil, it significantly increases soil pH ($P < 0.001$), exerting a liming-like ameliorative effect (Fig. 2). The primary mechanism involves the release of base ions (K^+ , Ca^{2+} , and Mg^{2+}) from biochar into the soil solution. These ions exchange with soil H^+ and active Al^{3+} , neutralizing soil acidity and reducing aluminum toxicity risks (Arwenyo et al., 2023; Tanure et al., 2026). Phosphogypsum combined with red mud enhances soil electrical conductivity. This occurs because phosphogypsum itself is rich in soluble Ca^{2+} and SO_4^{2-} , while red mud contains substantial soluble salts like Na^+ and SO_4^{2-} . Their synergistic dissolution rapidly increases soil solution ion concentration, significantly boosting EC (de Souza Costa et al., 2021). Applying phosphogypsum alone increases soil moisture content (Fig. 2), likely because calcium ions in phosphogypsum exchange with sodium ions in soil colloids, promoting the aggregation of dispersed fine soil particles into stable aggregate structures, creating more micro-pores in the soil and significantly enhancing its water-holding and retention capacity (Gao et al., 2025; Yamani et al., 2026).

Soil organic matter is a core indicator reflecting soil fertility levels and our results found that the application of phosphogypsum alone significantly increased SOM content (Fig. 2). Such an increase may occur due to the inherent organic matter deficiency and weak carbon sequestration capacity of saline-alkali soils. Under phosphogypsum amendment, the input of organic matter from aboveground residues and root segments into the soil markedly increased (Lu et al., 2023), further promoting organic matter accumulation and carbon mineralization rates. When phosphogypsum was combined with biochar, the enhancement effect on soil organic matter was even more pronounced, primarily attributed to biochar's composition of highly aromatized stable carbon, which resists degradation in soil, possesses a long average residence time, and directly expands the soil carbon pool. Concurrently, its porous structure and high specific surface area physically shield existing soil organic molecules, reducing microbial decomposition rates (Cao et al., 2025). Furthermore, the application of phosphogypsum alone

significantly increases soil available phosphorus, alkali-hydrolyzable nitrogen, ammonium nitrogen, total potassium, and total nitrogen content (Fig. 2), consistent with findings from multiple studies (Al-Enazy et al., 2018; Lu et al., 2023; Mu et al., 2024). The core mechanism likely stems from phosphogypsum's direct regulation of soil chemistry. On one hand, its acidic nature lowers soil pH, activates insoluble phosphates, and suppresses ammonia volatilization, shifting the $\text{NH}_3/\text{NH}_4^+$ chemical equilibrium toward NH_4^+ and thereby reducing gaseous nitrogen losses (Li et al., 2018). On the other hand, the released Ca^{2+} and SO_4^{2-} ions can liberate phosphorus immobilized by iron and aluminum through ion exchange, promoting the formation of more soluble Ca-P complexes and thereby increasing available phosphorus content (Al-Enazy et al., 2018). Simultaneously, these ions can form insoluble double salts like potassium calcium aluminate with NH_4^+ and K^+ , effectively reducing leaching and volatilization losses of nitrogen and potassium nutrients (Li et al., 2018). Furthermore, phosphogypsum may improve soil properties by supplementing elements such as sulfur, calcium, silicon, magnesium, and potassium. Therefore, such amendments create a new environment conducive to microbial growth and reproduction, thereby activating microbial activity, increasing microbial abundance, and improving microbial community structure. Such effects indirectly influence microbial-mediated nutrient cycling processes involving carbon, nitrogen, and phosphorus in soil, ultimately promoting the release of soil nutrients (Li et al., 2025; Palencia et al., 2024; Qi et al., 2023). Our study revealed that phosphogypsum application within the range of 10%–50% yielded the best improvement in soil nutrient status (Fig. 5). Furthermore, when phosphogypsum is applied in combination with biochar, compound fertilizer, or farmyard manure, nutrients also increase markedly which indicates synergistic interactions between phosphogypsum and exogenous additives, enabling more effective enhancement of soil nutrient conditions (Fig. 2).

Soil enzymes participate in material cycling and energy flow within soil ecosystems, and their activity reflects the strength of soil nutrient cycling capacity. The application of phosphogypsum alone significantly increased soil β -glucosidase and urease activity (Fig. 1a). This may be attributed to the Ca^{2+} , SO_4^{2-} , and trace soluble organic carbon contained in phosphogypsum itself, which provides exogenous energy and substrates for soil microorganisms, thereby directly stimulating microbial metabolic activity and promoting the synthesis of cellulose-degrading enzymes (e.g., β -glucosidase) and nitrogen-transforming enzymes (e.g., urease) (Tejada et al., 2006). Furthermore, calcium ions in phosphogypsum promote the binding of soil organic matter to mineral particles through “cation bridging”, thereby enhancing the formation and stability of microaggregates (Shao et al., 2026). Microaggregates improve soil pore structure and aeration, creating a more favorable microenvironment for microbial activity and enzyme function (Bronick and Lal., 2005). Our findings indicated that phosphogypsum application reduces α -diversity in soil microbial communities (Fig. 1c). This reduction may result from increased soil salinity and electrical conductivity due to calcium sulfate dissolution in phosphogypsum, which causes generalized osmotic stress on microorganisms (Rath and Rousk., 2015). Additionally, trace impurities commonly present in phosphogypsum, such as fluoride and heavy metals (Tayibi et al., 2009), may exert toxic effects on microorganisms, leading to reduced abundance of numerous non-tolerant taxa.

- Effects of phosphogypsum on plant growth

Plant growth and physiological indicators ultimately reflect the agronomic benefits of soil improvement measures. Phosphogypsum combined with compound fertilizers or farmyard manure demonstrated significant synergistic yield-enhancing effects (Fig. 7). This may stem from their functionally complementary nature. Although phosphogypsum has multiple functions in soil improvement, such as improving soil aggregate structure and supplementing medium nutrients like calcium and sulfur, its content of major macronutrients such as nitrogen and potassium is extremely low, making it difficult to meet the high-intensity and concentrated nutrient demands of crops during their critical growth periods, such as the rapid growth stage and the yield formation stage. The addition of compound fertilizer or farmyard manure directly bridges this nutritional gap, supplying crops with sufficient and readily available core nutrients (Duan et al., 2023). The application of phosphogypsum alone significantly ($P < 0.001$) enhanced plant biomass, plant height, and root length (Fig. 3). This positive effect is mainly attributed to the following synergistic mechanisms: First, phosphogypsum significantly improves soil physical structure and pore distribution by alleviating aluminum toxicity, displacing exchangeable sodium ions and promoting soil aggregate stabilization, thereby enhancing soil aeration and water-holding capacity, and creating a more favorable microenvironment for root development (Mezlini et al., 2026). Second, as a direct source of calcium and sulfur that plants can absorb and utilize, phosphogypsum participates in key physiological processes such as protein synthesis, enzyme activity regulation, and the deposition of cell wall polysaccharides and lignin (Xiang et al., 2022). While correcting calcium and sulfur deficiencies, it drove plant morphogenesis and efficient biomass accumulation (Caires et al., 2011). Furthermore, when phosphogypsum is applied in combination with biochar, compound fertilizers, or farmyard manure with wood peat, these nutrients also show a significant increase that indicates synergistic interactions between phosphogypsum and external additives, enabling more effective promotion of plant growth and development. Regarding ion balance regulation, phosphogypsum combined with compound fertilizers simultaneously increased K^+ and Ca^{2+} content while significantly reducing Na^+ content (Fig. 3). This likely occurs because the Ca^{2+} -rich phosphogypsum displaced Na^+ from soil colloids, effectively reducing sodium toxicity while creating adsorption sites for potassium ions (Oliveira et al., 2024). Such synergy with exogenous potassium fertilizers simultaneously achieved “potassium promotion and sodium removal” for saline-alkali improvement and nutrient enhancement (Pesini et al., 2025). In contrast, applying phosphogypsum alone significantly increased Ca^{2+} content but had no significant regulatory effect on K^+ and Na^+ , indicating its ameliorative effect is primarily limited to calcium supplementation (Fig. 3). Notably, although the combined application of phosphogypsum and red mud can provide calcium sources in a synergistic manner, it significantly aggravated the accumulation of sodium ions in the soil (Fig. 3). This phenomenon mainly results from the inherent strong alkalinity and high water-soluble sodium salt content (such as Na_2CO_3 , $NaAl(OH)_4$, etc.) of red mud (Xiao et al., 2022). During the mixed application process, the Ca^{2+} released by phosphogypsum can partially replace the adsorbed Na^+ on soil colloids through cation exchange; however, the large amount of soluble sodium carried by red mud far exceeds the capacity that can be displaced by Ca^{2+} or subsequently removed by leaching, ultimately leading to a significant increase in the effective sodium concentration in the soil (Outbakat et al., 2022).

In terms of plant physiology, the application of phosphogypsum alone significantly increased chlorophyll content and the activity of superoxide dismutase and catalase (Figs. 1 and 3). The increase in chlorophyll content may be related to the enrichment of nutrients such as phosphorus, sulfur, and calcium in phosphogypsum. These nutrients promote plant growth and productivity by participating in cellular respiration, photosynthesis, protein synthesis, and various enzymatic reactions (Rutherford et al., 1994). Simultaneously, the acidifying effect of phosphogypsum in the rhizosphere may have increased the availability of iron and manganese, and iron is an essential micronutrient for chlorophyll biosynthesis and the formation of thylakoids and grana (Smaoui-Jardak et al., 2017). Besides, the significant increase in SOD and CAT activity indicates that plants activated antioxidant defense systems to counter oxidative stress after phosphogypsum application (Fig. 3). Phosphogypsum contains heavy metals like cadmium and chromium, whose accumulation in soil can induce reactive oxygen species (ROS) production (Wang et al., 2024). As the first line of antioxidant enzymes, SOD decomposes superoxide radicals into oxygen and hydrogen peroxide, while CAT further decomposes hydrogen peroxide into water and oxygen, thereby mitigating cellular damage caused by membrane lipid peroxidation products (Rajput et al., 2021). Therefore, elevated SOD and CAT activities enhance plant cells' capacity to scavenge free radicals and mitigate membrane lipid peroxidation damage. Such enzymatic activities effectively reduce oxidative stress induced by heavy metals and other stressors in phosphogypsum, thereby improving physiological adaptation and stress tolerance under adverse conditions (Binglei et al., 2023).

Conclusion

This meta-analysis based on 44 independent case studies indicated that the application of phosphogypsum significantly alters soil physical and chemical properties and biological functions, thereby promoting plant growth and development. The results showed that the application of phosphogypsum alone reduced soil pH but increased organic matter and field water holding capacity, and significantly enhanced the mineralization and transformation efficiency of key nutrients such as nitrogen, phosphorus, and potassium by increasing the activities of β -glucosidase and urease. Correspondingly, plant biomass, plant height, root length, chlorophyll content, and antioxidant enzyme activity showed significant increases. Compared with application of phosphogypsum alone, the combined application of phosphogypsum and biochar alleviated the acidification effect, and further synergistically increased soil organic matter reserves, available potassium content, and aboveground and underground plant biomass. The combined application of phosphogypsum with compound fertilizer or farmyard manure optimized the adsorption-desorption balance of K^+ , Ca^{2+} , and Na^+ through ion interaction mechanisms, significantly increasing crop yields. It should be particularly noted that the combined application of phosphogypsum and red mud poses significant ecological risks: the high concentration of soluble sodium salts carried by red mud can easily lead to soil sodium accumulation and increased electrical conductivity, exacerbating secondary salinization and structural degradation such as surface crusting. In addition, to balance soil nutrient retention capacity and robust plant growth, it is recommended to control the application rate of phosphogypsum within a reasonable range of 10% to 50%. This meta-analysis systematically clarified the comprehensive impact mechanism of

phosphogypsum on soil multi-dimensional properties and plant physiological responses, providing a solid theoretical basis and quantitative data support for the scientific assessment of its application potential in saline-alkali land improvement, nutrient management, and sustainable agriculture.

Declarations

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Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors' Contribution

Zhengli Feng wrote the first draft of the manuscript and collected the data. Jianping Shen, Yingfu Zhu and Jun Bi analyzed the data. Hui Zhang, Syed Turab Raza and Yong Liu contributed to the methodology and visualization. Ping Li and Zhe Chen supervised the research, secured funding, and revised the manuscript. All authors reviewed and approved the final manuscript.

Data Availability

The datasets generated during and/or analysed during the current study are available from the corresponding author upon reasonable request.

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Figures

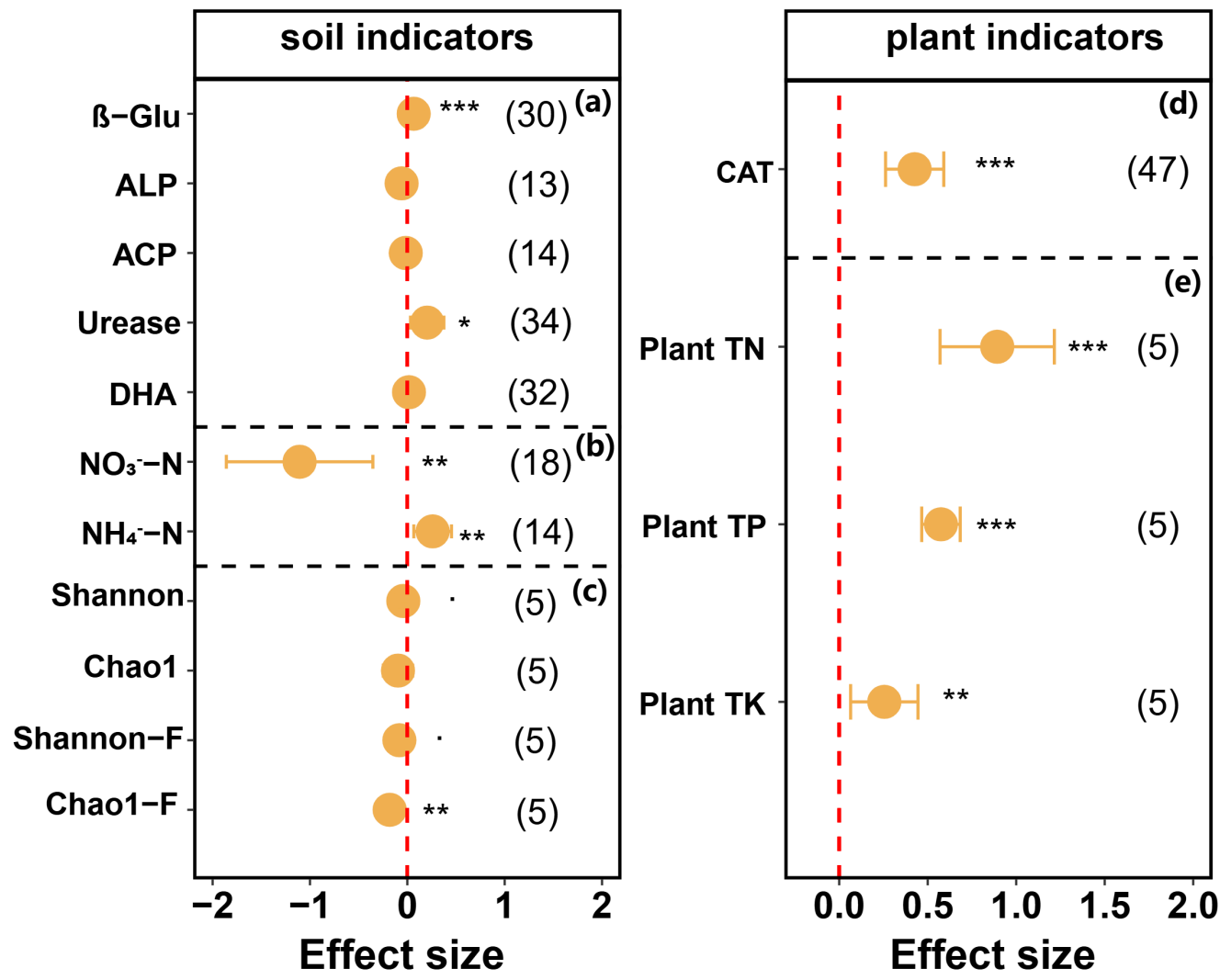


Figure 1

Effects of phosphogypsum application alone on key soil enzyme activities (a), inorganic nitrogen components (b), microbial α -diversity index (c), plant catalase activity (d), and nutrients (e). β -Glu, β -glucosidase activity; ALP, alkaline phosphatase activity; ACP, acid phosphatase activity; Urease, urease activity; DHA, dehydrogenase activity; NO_3^- -N, nitrate nitrogen content; NH_4^+ -N, ammonium nitrogen content; Shannon, bacterial Shannon index; Chao1, bacterial Chao1 index; Shannon-F, fungal Shannon index; Chao1-F, fungal Chao1 index; CAT, catalase activity; Plant TN, total nitrogen in plants; Plant TP, total phosphorus in plants; Plant TK, total potassium in plants.

Error bars indicate 95% confidence intervals (CI). Numbers in parentheses denote sample sizes for each variable. * Indicates significant differences compared with the control (without phosphogypsum application): * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

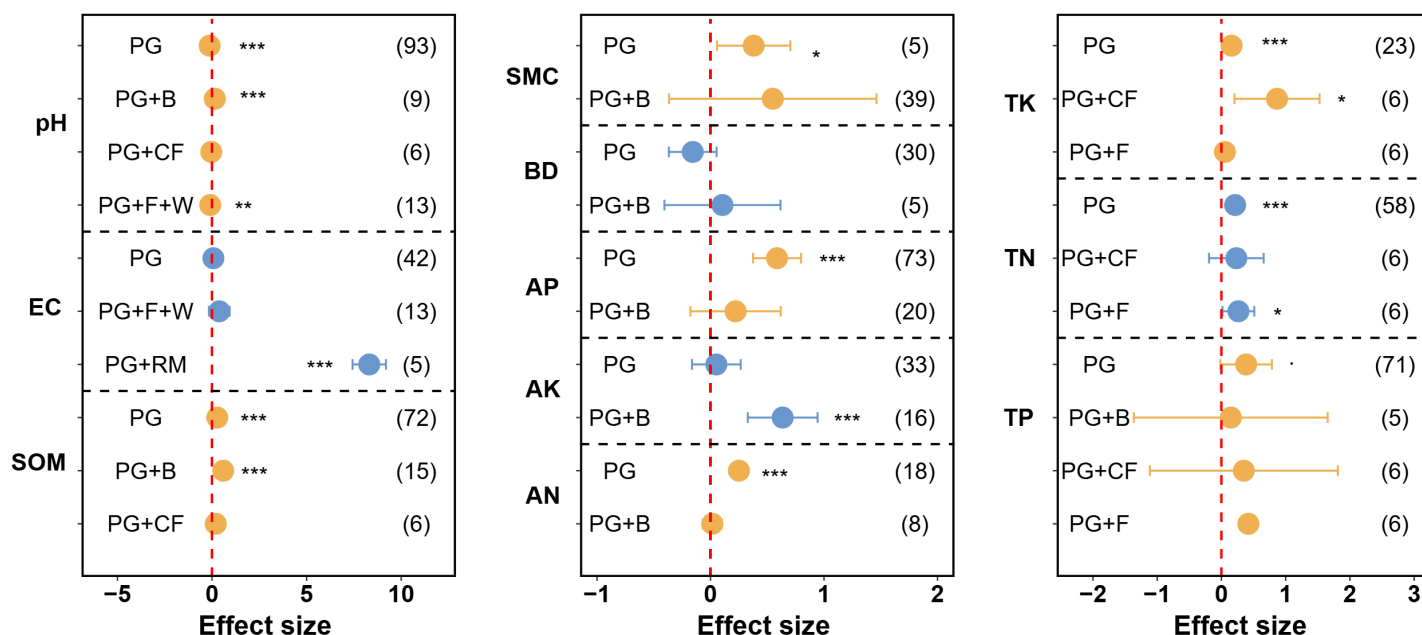


Figure 2

Effects of different phosphogypsum combinations on soil nutrients and physicochemical fertility. PG: Phosphogypsum alone; PG + B: Phosphogypsum combined with biochar; PG + B + L: Phosphogypsum combined with biochar and lime; PG + CF: Phosphogypsum combined with compound fertilizer; PG + F: Phosphogypsum combined with farmyard manure; PG + F + W, phosphogypsum mixed with farmyard manure and wood peat; PG + RM, phosphogypsum mixed with red mud; PG + B + CF, phosphogypsum mixed with biochar and compound fertilizer. pH, soil acidity/alkalinity; EC, electrical conductivity; SOM, soil organic matter; SMC, soil moisture content; BD, bulk density; AN, alkali-hydrolyzable nitrogen; AP, available phosphorus; AK, available potassium; TN, total nitrogen; TP, total phosphorus; TK, total potassium.

Error bars indicate 95% confidence intervals (CI); Numbers in parentheses denote sample sizes for each variable. * Indicates significant differences compared to the control (without phosphogypsum application): * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

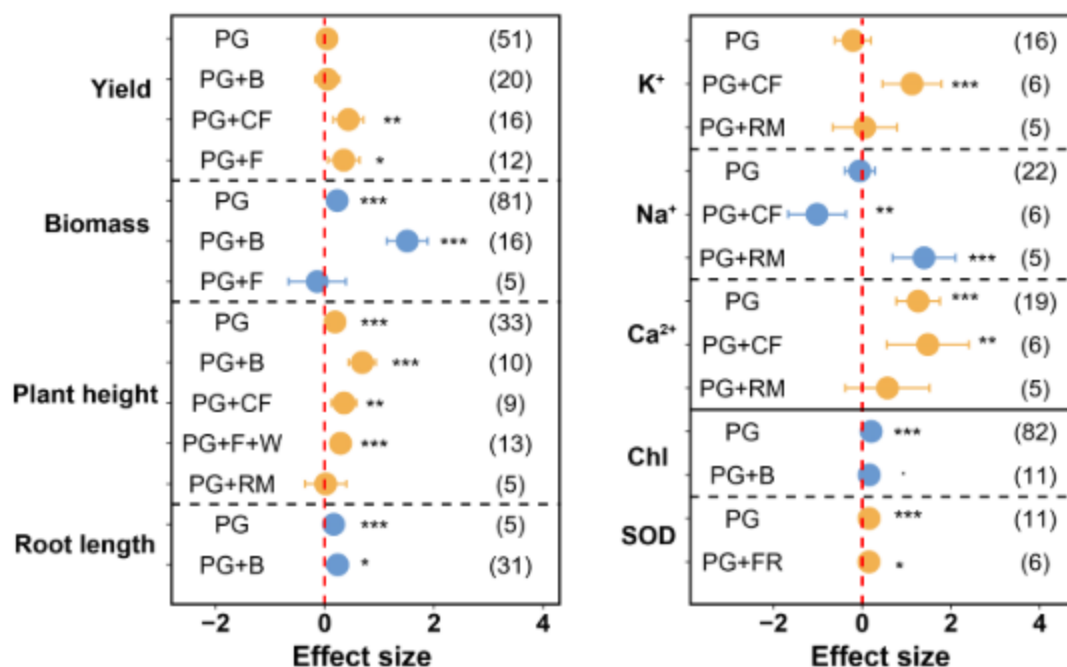


Figure 3

Effects of different phosphogypsum compound treatments on plant growth traits and physiological parameters. PG: phosphogypsum alone; PG + B: phosphogypsum combined with biochar; PG + CF: phosphogypsum combined with compound fertilizer; PG + F: phosphogypsum combined with farmyard manure; PG + F + W: phosphogypsum combined with farmyard manure and wood peat; PG + RM, phosphogypsum combined with red mud; PG + B + CF, phosphogypsum combined with biochar and compound fertilizer); PG + FR, phosphogypsum combined with furfural residue; Yield, Crop yield; Biomass, biomass; Plant height, plant height; Root length, root length; K⁺, potassium ion content; Na⁺, sodium ion content; Ca²⁺, calcium ion content; Chl, chlorophyll content; SOD, superoxide dismutase activity. Error bars indicate 95% confidence intervals (CI). Numbers in parentheses denote sample sizes for each variable. * Denotes significant differences compared to the control (no phosphogypsum application): * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

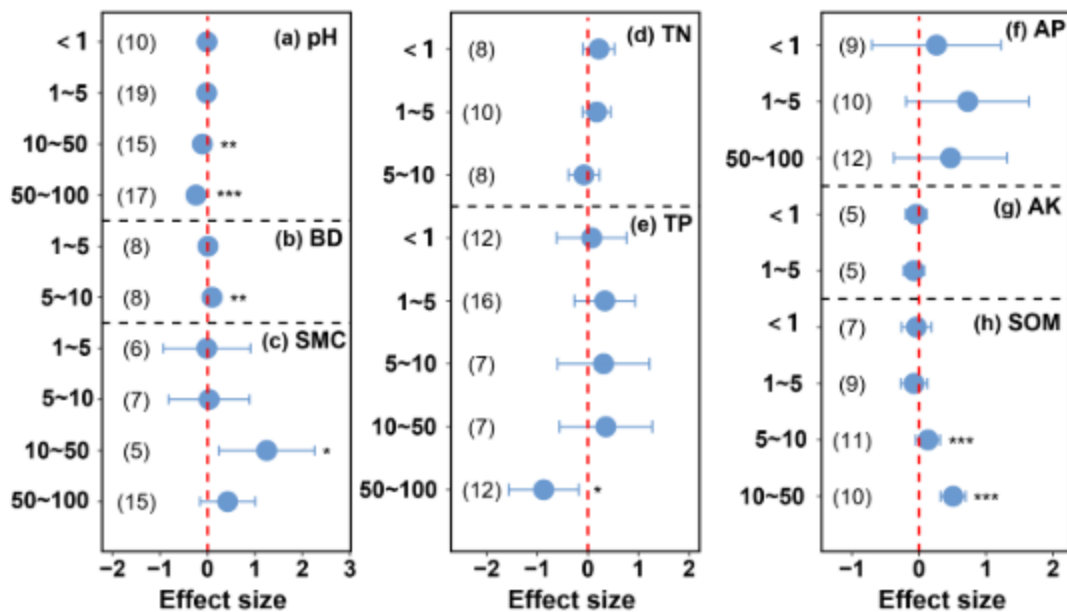


Figure 4

Effects of phosphogypsum application rates on soil pH (a), bulk density (b), moisture content (c), total nitrogen (d), total phosphorus (e), available phosphorus (f), available potassium (g), and soil organic matter (h). n denotes the sample size for each variable. Mean effects and 95% confidence intervals (CI) are shown.

If the CI does not overlap with the 0 line, the effect is significant ($P < 0.05$). * indicates a significant effect of phosphogypsum application ($P < 0.05$), ** indicates a significant effect ($P < 0.01$), and *** indicates a highly significant effect ($P < 0.001$).

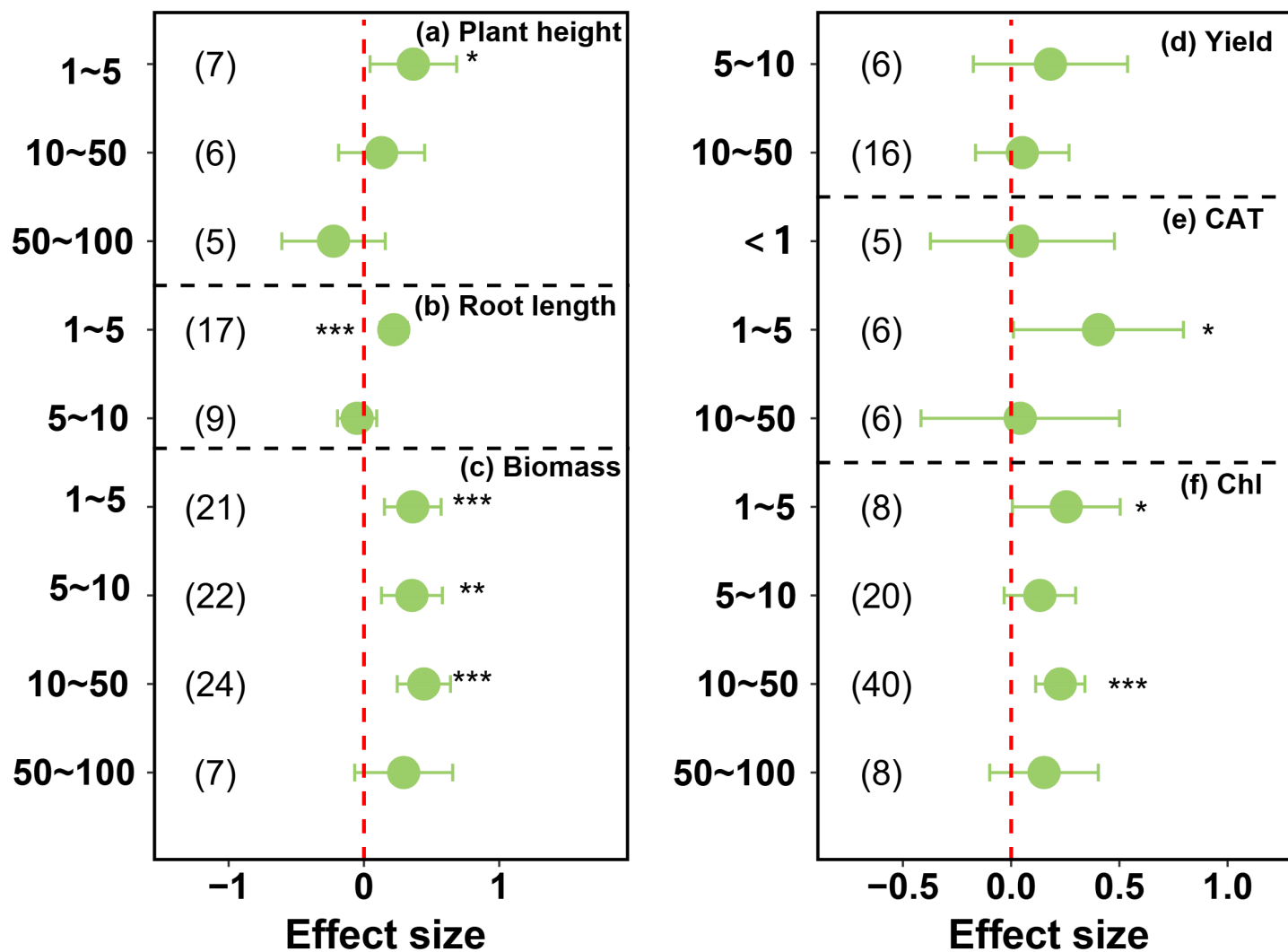


Figure 5

Effects of phosphogypsum application rates on plant height (a), root length (b), biomass (c), yield (d), catalase activity (e), and chlorophyll content (f). n denotes sample size for each variable; displays mean effects and 95% confidence intervals (CI).

If the CI does not overlap with the 0 line, the effect is significant ($P < 0.05$); * indicates a significant effect of phosphogypsum application ($P < 0.05$); ** indicates a significant effect of phosphogypsum application ($P < 0.01$); *** indicates a highly significant effect of phosphogypsum application ($P < 0.001$).

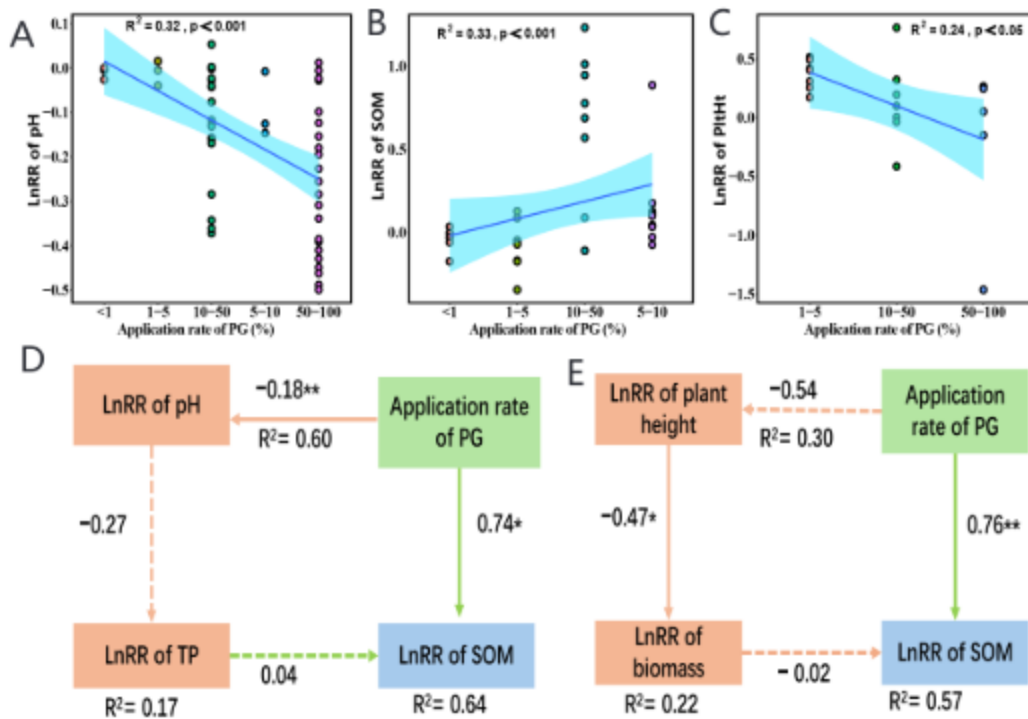


Figure 6

Relationship between phosphogypsum application rate and soil pH, organic matter, and plant height. LnRR denotes the natural logarithm of the response ratio between phosphogypsum-treated and control groups (A-C). SEM reveals the effect of phosphogypsum application rate on SOM through response ratios (LnRR) of soil pH, total phosphorus, plant height, and biomass. Arrows indicate the direction of hypothesized causal relationships. Positive correlations are indicated by green arrows, negative correlations by orange arrows, and dashed arrows denote non-significant correlations. Numbers on arrows represent normalization factors, and R^2 indicates the percentage of variance explained. * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$ (D, E).

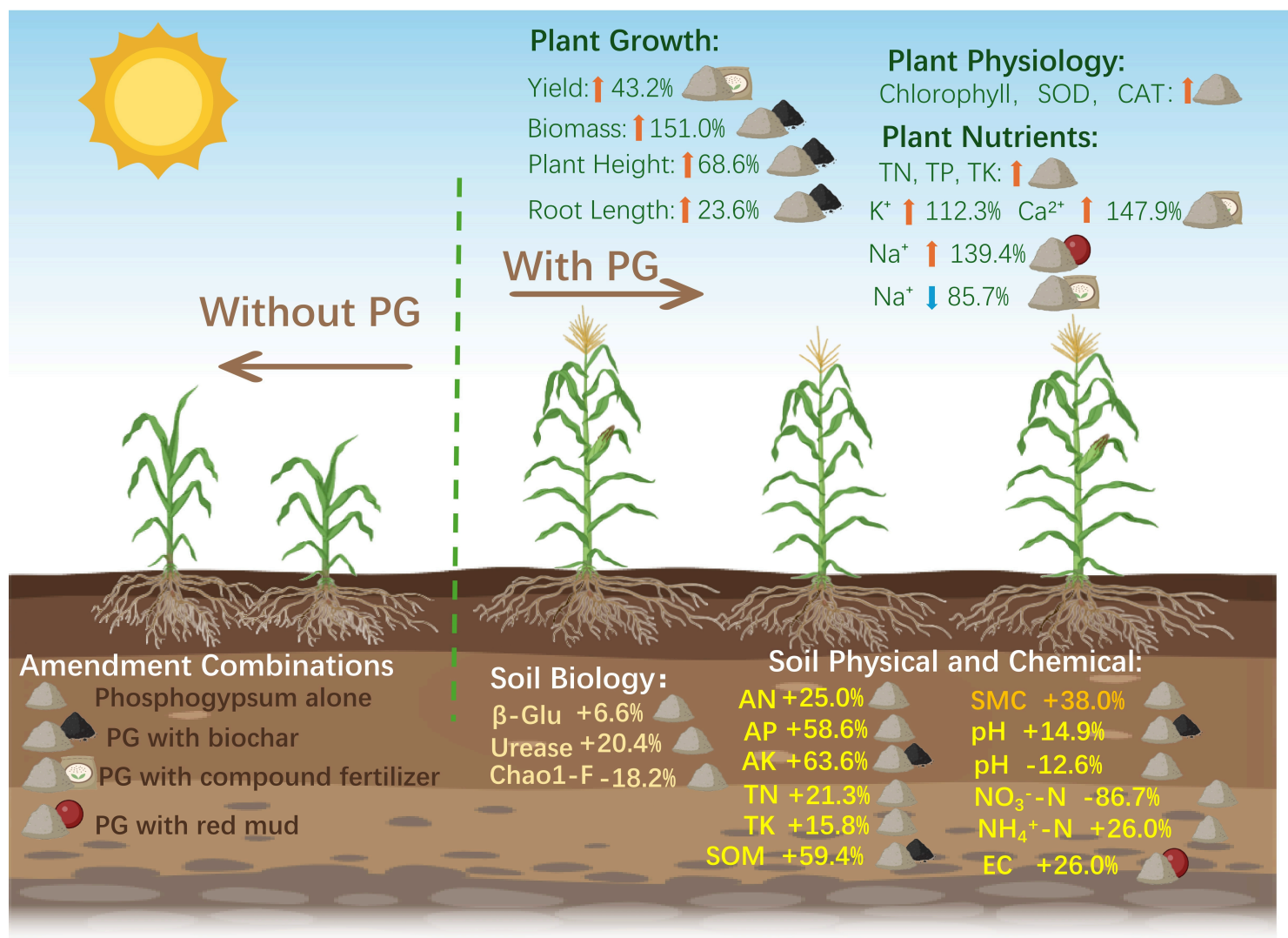


Figure 7

Conceptual diagram illustrates the impacts of PG on soil physicochemical properties and plant growth. The values show the changes after using PG.

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