

Calcium silicate effects on wheat phosphorus nutrition depend on phosphorus-source chemistry

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Abstract

Purpose Silicon (Si) amendments can improve crop phosphorus (P) nutrition, but the effect is inconsistent. We tested whether wheat's response to a calcium-silicate amendment depends on the chemical form of P supplied, in a factorial sand-culture experiment.

Methods Wheat (*Triticum aestivum* cv. Omer) was grown in sand culture with soluble KH_2PO_4 , hydroxyapatite (HA), FePO_4 or no added P (NoP), each with or without CaSiO_3 . CaCl_2 balanced calcium in the NoSi treatments. Shoot and root biomass, the shoot ionome, root architecture and soluble phosphate in an abiotic sand-mineral assay were measured.

Results CaSiO_3 effects depended strongly on P source, and the response mode differed among sources. On hydroxyapatite, the limiting source, CaSiO_3 drove growth and P uptake, increasing shoot biomass by 85%, root biomass by 86% and estimated shoot P content by 56%, with a larger, coarser root system. On soluble KH_2PO_4 it drove growth, increasing shoot biomass by 65%. On FePO_4 , already high-biomass, CaSiO_3 produced only a weak, non-significant trend but raised shoot Fe and Mn by 49 and 119%. With no added P it had little effect. An abiotic assay showed CaSiO_3 raised pH and conductivity but decreased soluble $\text{PO}_4\text{-P}$ by 79 to 98%.

Conclusion A single calcium-silicate amendment produced several P-source-dependent response modes rather than one generic effect. The abiotic assay showed that CaSiO_3 locked up rather than released phosphate, so the hydroxyapatite response points to plant- and rhizosphere-mediated acquisition rather than bulk phosphate release.

1 Introduction

Phosphorus (P) is an essential macronutrient for crop production, and plants acquire it almost entirely as orthophosphate from the soil solution [1]. Global crop production depends heavily on P fertilizer manufactured from mined phosphate rock, a finite and unevenly distributed resource [2]. Repeated fertilization has built large legacy P pools in many agricultural soils, yet much of this P is chemically bound and poorly available to roots [3]. Improving crop access to sparingly soluble and legacy P is therefore central to more efficient P use [3].

The availability of inorganic P is governed by sorption and desorption and by precipitation and dissolution [1]. These reactions are controlled by soil pH and by the calcium- and iron-bearing minerals that bind phosphate, so P solubility depends on the chemical form in which P occurs [1]. Sparingly soluble calcium phosphates dominate in alkaline and calcareous soils, whereas iron- and aluminium-bound phosphates dominate in acid and oxide-rich soils [1]. Hydroxyapatite and FePO_4 are widely used as model calcium- and iron-bound P sources to compare plant access to these contrasting pools [4, 5]. Their solubility is set by different reactions, so each source imposes its own acquisition problem for the plant [5].

Roots acquire sparingly soluble P both by exploring the soil with a larger root system and by modifying the rhizosphere [1]. Root uptake, proton and bicarbonate release, respiration and microbial activity shift the local sorption and dissolution equilibria that set phosphate solubility at the root surface [1]. Roots also release carboxylates such as citrate, malate and oxalate as exudates, which mobilize P by ligand exchange and by complexing the metal cations that bind it [6]. Among these routes, wheat has been shown to cope with low P chiefly by maintaining root biomass and length, with fine-root allocation changing across the P-deficiency gradient, rather than by increasing rhizosphere acidification or acid-phosphatase activity [7].

Silicon (Si) is a beneficial element for many plants, with especially consistent effects in grasses and cereals [8]. Wheat takes up Si actively through the Si transporter *TaLsi1* [9], a homologue of the rice transporter *Lsi1* [10]. Si supply stimulates the wheat root system, increasing root length and lateral rooting [11], and modifies root morphology across many crop species [12].

Reported effects of Si on crop P nutrition are not uniform. Silicon has been reviewed as a strategy to mitigate phosphate deficiency in cereals [13] and a meta-analysis of Si-P fertilization experiments found an overall 52% increase in plant P uptake. However, the effect ranged widely among crops and soils and was absent in some studies [14]. In wheat grown under low-P acid soil conditions, Si increased P accumulation alongside changes in rhizosphere pH and root phosphate-transporter expression [15], and Si together with phosphate-solubilizing bacteria raised wheat P status under both soluble and rock-phosphate supply [16]. Si can also act on the soil itself, mobilizing phosphate from iron-mineral surfaces and so raising soil P availability [17]. Si has also been reported to restrain rather than promote P accumulation when P is plentiful [18, 19].

How wheat responds to a Si amendment may itself depend on the chemical form of P supplied, because P sources of contrasting solubility present different acquisition problems [1, 5]. Whether the wheat response depends on P-source chemistry has so far been probed only with combined Si and phosphate-solubilizing-bacteria treatments and a single soluble-versus-rock-phosphate contrast [16]. To the best of our knowledge, a calcium-silicate amendment has not been tested across multiple P sources of defined, contrasting chemistry in wheat. With this in mind, we grew wheat with four phosphorus sources of contrasting chemistry, soluble KH_2PO_4 , hydroxyapatite, FePO_4 and no added P, each with or without a Si amendment supplied as calcium silicate. We measured growth, the shoot ionome, root architecture and soluble phosphate release in a parallel abiotic assay. We hypothesized that the wheat response to the Si amendment would differ among these P sources.

2 Materials and methods

2.1 Plant material and growth conditions

Seeds of bread wheat (*Triticum aestivum* L. cv. Omer) were a standard commercial lot carrying a fungicidal seed dressing, and were sown directly into 1 L pots containing quartz sand, five seeds per pot.

Plants were grown in a greenhouse under a 16/8 h light/dark photoperiod and irrigated daily with a modified half-strength, phosphorus-free Hoagland solution. P was supplied solely through the assigned P-source treatments. The quartz sand was characterized for background plant-available nutrients by CaCl_2 and acetic-acid extraction with ICP-OES determination ($n = 4$). CaCl_2 -extractable (soluble) P was below detection ($< 0.01 \text{ mg L}^{-1}$) and CaCl_2 -extractable Si was low (mean 1.5 mg L^{-1}), indicating a phosphorus-poor, low-Si medium.

2.2 Experimental design

Two runs were conducted. Run 2 is the primary dataset and crossed CaSiO_3 status (NoSi, Si) with four P sources (KH_2PO_4 , HA, FePO_4 , NoP), giving eight treatment combinations. Run 1 crossed the amendment with three P sources (KH_2PO_4 , HA, FePO_4) and is reported as a cross-check (Table S1). The two runs were analysed separately rather than pooled, with Run 1 providing an independent check on the direction of the principal effects. In Run 2, shoot biomass was available for 6–7 pots per treatment, and root biomass and shoot ICP-OES data for 4 pots per treatment. Response-specific sample sizes per treatment cell are given in Table S2.

2.3 Phosphorus sources and calcium-silicate amendment

Four P-source treatments were used: KH_2PO_4 as a soluble-P positive control, no added P (NoP) as a negative control, and two sparingly soluble minerals of contrasting chemistry, hydroxyapatite (HA; $\text{Ca}_5(\text{PO}_4)_3\text{OH}$), a calcium phosphate, and $\text{FePO}_4 \cdot 2\text{H}_2\text{O}$ (referred to as FePO_4 below), an iron phosphate. HA was applied at 0.21 g kg^{-1} sand and $\text{FePO}_4 \cdot 2\text{H}_2\text{O}$ at 0.24 g kg^{-1} sand, giving near-equivalent elemental P additions for the two mineral P sources. KH_2PO_4 was applied at 0.3 g kg^{-1} sand as a soluble-P positive control. Compound rates and co-supplied elements are given in Table S3. Si was supplied as calcium silicate mixed into the sand before pot assembly at $10.68 \text{ mmol Si kg}^{-1}$ sand ($1.24 \text{ g CaSiO}_3 \text{ kg}^{-1}$ sand). CaCl_2 was added to the corresponding NoSi treatments to balance the calcium supplied with CaSiO_3 , so the comparison separates the CaSiO_3 amendment from simple calcium addition.

2.4 Harvest and biomass

At 15 days, one of the five plants per pot was harvested destructively, and at 30 days the remaining four were harvested together. Shoots and roots were separated. Roots were washed free of sand under running water and stored in alcohol, scanned for architecture (below), then oven-dried. Shoots were oven-dried directly. Drying was at 70°C for 72 h, and shoot dry weight, root dry weight and root-to-shoot ratio were recorded.

2.5 Root architecture

Before drying, the alcohol-stored root system from each pot was spread in water and imaged with an Epson Expression 11000XL flatbed scanner at 400 dpi, and analysed with WinRHIZO software (Regent Instruments, Canada). Total root length, surface area, average diameter, root volume, root tips and forks,

and root length within diameter classes (fine roots defined as diameter ≤ 0.5 mm) were measured. One scan with a conflicting pot identity was excluded, and a sensitivity analysis across scan-record exclusion scenarios is reported in Table S4.

2.6 Shoot elemental analysis and estimated content

Dried shoot subsamples were acid-digested in concentrated $\text{HNO}_3\text{:H}_2\text{O}_2$ (10:1, v/v). Shoot concentrations of P, Al, Ca, Fe, K, Mg, Mn, Na, Zn and S, together with operational acid-recovered Si, were determined by inductively coupled plasma optical emission spectrometry (ICP-OES; SPECTROGREEN, SPECTRO Analytical Instruments GmbH, Kleve, Germany) and are reported as mg kg^{-1} dry weight. Estimated shoot element content was calculated as shoot concentration multiplied by the treatment-cell mean shoot dry mass per plant from the full shoot-biomass dataset (not only the ICP-analysed pots), and is reported as $\mu\text{g plant}^{-1}$. Si measurements were included for completeness but should not be read as total plant Si, since plant Si is largely amorphous silica that nitric-acid digestion does not fully recover [20].

2.7 Abiotic sand-mineral assay

A separate abiotic assay tested whether CaSiO_3 altered solution chemistry in the same sand and mineral-P system. Quartz sand (5 g) was incubated with HA or FePO_4 and 0, 1.5, 2.5 or 5.0 mM CaSiO_3 , and the 2.5 mM level corresponds to the plant-experiment dose. Solution pH and electrical conductivity (EC) were measured at 24, 96 and 189 h, and soluble $\text{PO}_4\text{-P}$ colorimetrically at 882 nm for the 96 and 189 h samples, with three replicates per mineral, dose and time combination.

2.8 Statistical analysis

For each plant endpoint, a two-way ANOVA tested P source, CaSiO_3 treatment and their interaction. Because the factorial model and the biological question address different comparisons, planned within-source NoSi versus CaSiO_3 contrasts were also evaluated by Welch's *t* test. For figure annotations, these planned contrasts were Holm-adjusted within each panel; unadjusted *P* values and effect sizes are reported in the text or supplementary source tables where specific contrasts are discussed. Shoot P concentration and the P, Fe and Mn content endpoints were analysed on $\log_{10}$ -transformed values to meet the normality and equal-variance assumptions of ANOVA. Plotted values remain on the original scale. Each content value combines a shoot concentration with the treatment-cell mean shoot mass, so its variance reflects concentration rather than plant-to-plant biomass variation, and content endpoints are read as directional accumulation measures. Abiotic $\text{PO}_4\text{-P}$ was analysed separately for each time point on $\log_{10}$ -transformed concentration, with mineral, CaSiO_3 dose and their interaction as fixed effects. For the abiotic dose-response experiment, CaSiO_3 doses of 1.5, 2.5 and 5.0 mM were compared with the 0 mM control within each mineral and time point by planned Welch contrasts on $\log_{10}$ -transformed values, with Holm adjustment within each mineral-time family for figure annotations. Benjamini-Hochberg false-discovery-rate *q* values are provided for the full ionome and the main root-architecture family (Tables S5, S6). All tests were two-sided, and analyses were performed in Python with

pandas, scipy, statsmodels, seaborn and matplotlib. Shoot and root biomass were expressed per pot. Because established plants per pot varied, plants per pot was added as a covariate to the biomass models as a sensitivity check on the CaSiO_3 effects (Table S7).

2.9 Use of generative AI

During the preparation of this manuscript the authors used generative AI tools (OpenAI ChatGPT/Codex and Anthropic Claude) to assist with drafting and language editing, with code-supported checking of the statistical analyses and figures, and with reference formatting and verification. The AI tools did not design the study, generate or alter any data or results, or make scientific decisions. The authors verified all data, analyses, figures, and citations, edited the text, and take full responsibility for the content.

3 Results

3.1 P sources established contrasting baseline growth states

The P-source controls established distinct baseline growth states (Fig. 1A, B). Without CaSiO_3 , FePO_4 did not produce a low-P condition. Shoot biomass averaged 2.96 g pot^{-1} , nearly double the NoP control, and root biomass fell in the high-biomass group. HA without CaSiO_3 produced low shoot and root biomass, statistically grouped with NoP. The mineral-P treatments therefore did not create a single insoluble-P condition. HA behaved as the limiting mineral P source, whereas FePO_4 supported high biomass under these sand-culture conditions. The HA and FePO_4 mineral treatments supplied near-equivalent elemental P rates (Table S3), so this contrast reflects mineral-source availability rather than unequal mineral-P loading.

3.2 CaSiO_3 effects on growth depended on P source

Growth responses to CaSiO_3 depended strongly on this baseline (Fig. 1A, B), and the shoot biomass interaction was significant ($P = 0.0047$). CaSiO_3 increased shoot biomass strongly under both HA, from 1.34 to 2.48 g pot^{-1} (+ 85%; $P = 4.6 \times 10^{-6}$), and KH_2PO_4 , from 2.15 to 3.55 g pot^{-1} (+ 65%; $P = 0.0074$). On HA it also increased root biomass from 0.36 to 0.68 g pot^{-1} (+ 86%; $P = 0.0061$), whereas root biomass did not change under KH_2PO_4 . On FePO_4 , biomass was already high without CaSiO_3 and the additional response was small and not significant (+ 19%; $P = 0.082$), and NoP showed no significant biomass response (+ 8%; $P = 0.37$). The growth response to CaSiO_3 therefore differed among P sources, being large on HA and KH_2PO_4 , small on FePO_4 and absent on NoP.

Established plants per pot differed with the amendment, averaging 4.8 in the CaSiO_3 pots and 4.1 in the NoSi pots across the phosphorus-supplied sources ($P = 0.010$). This did not drive the growth response. Within hydroxyapatite, where growth is phosphorus-capped, pot biomass was independent of the

number of plants ($P = 0.88$), and including plants per pot as a covariate left the CaSiO_3 biomass effect essentially unchanged in every P source (Table S7).

3.3 Shoot P concentration and estimated content separated concentration from accumulation

Shoot P concentration and estimated shoot P content gave related but distinct responses (Fig. 2A, D). Shoot P concentration varied with P source ($P = 0.0156$), whereas the CaSiO_3 main effect was borderline ($P = 0.059$) and the interaction was not significant ($P = 0.137$). The HA within-source contrast was clean, and CaSiO_3 increased shoot P concentration from 612 to 691 mg kg^{-1} (+ 13%; $P = 0.0034$). FePO_4 showed a smaller concentration response that did not reach significance (+ 8%; $P = 0.082$) from an already high baseline. Estimated shoot P content showed a stronger CaSiO_3 main effect ($P = 0.0086$). On HA, the modest concentration increase translated into a larger content increase, from 238 to 371 $\mu\text{g plant}^{-1}$ (+ 56%; $P = 1.5 \times 10^{-5}$), because the treatment-cell mean shoot mass also increased. FePO_4 content was already high without CaSiO_3 (819 $\mu\text{g plant}^{-1}$) and rose by 16% ($P = 0.013$).

Shoot Fe and Mn showed a different response mode in the same figure (Fig. 2B, C, E, F). Shoot Fe concentration showed a strong P source by CaSiO_3 interaction ($P = 3.8 \times 10^{-6}$). CaSiO_3 increased Fe most on FePO_4 (+ 49%; $P = 8.0 \times 10^{-5}$) and HA (+ 40%; $P = 0.0014$), and estimated Fe content increased by 93% on HA and 59% on FePO_4 . Shoot Mn concentration also increased under CaSiO_3 ($P = 6.4 \times 10^{-4}$), with large within-source contrasts on FePO_4 (+ 119%; $P = 0.0014$) and HA (+ 54%; $P = 5.2 \times 10^{-4}$), and estimated Mn content increased by 135% on FePO_4 and 112% on HA. Thus, HA combined growth and P accumulation, whereas FePO_4 , where P status was already high, showed mainly Fe and Mn accumulation.

3.4 Root form changed most clearly under HA

Day-30 root architecture differed by P source and CaSiO_3 treatment (Fig. 3). Total root length differed by P source ($P = 3.8 \times 10^{-4}$) and CaSiO_3 ($P = 3.7 \times 10^{-4}$), with the strongest within-source increase on KH_2PO_4 (2998 to 4673 cm, + 56%; $P = 0.031$). The HA increase in total length was small and not significant (+ 15%; $P = 0.21$). Surface area increased on both KH_2PO_4 (+ 47%; $P = 0.024$) and HA (+ 33%; $P = 0.032$). Average diameter showed a significant P source by CaSiO_3 interaction ($P = 0.0278$). The HA contrast was the strongest root-form signal, increasing diameter from 0.371 to 0.426 mm (+ 15%; $P = 5.0 \times 10^{-4}$), whereas KH_2PO_4 and FePO_4 did not thicken. Root volume increased on HA (+ 52%; $P = 0.0075$) and KH_2PO_4 (+ 38%; $P = 0.024$). After Benjamini-Hochberg correction across the root-trait family, only the HA diameter increase survived ($q = 0.008$). The HA surface-area and volume increases were directionally consistent but did not survive correction ($q = 0.086$ and $q = 0.060$, Table S6). CaSiO_3 therefore did not impose one root phenotype. HA developed a larger and coarser root system, whereas KH_2PO_4 increased

root length, area and volume without a matching root-mass increase, indicating more and possibly finer roots rather than added root mass.

3.5 The abiotic assay showed that CaSiO_3 decreased soluble $\text{PO}_4\text{-P}$

The abiotic assay confirmed that CaSiO_3 strongly altered solution chemistry. At the plant-experiment dose of 2.5 mM, pH was 9.85 in HA and 9.80 in FePO_4 at 24 h, rising to 10.08 and 10.03 by 189 h, against pH 7.60 in HA and 8.61 in FePO_4 without CaSiO_3 at 24 h. EC increased with dose and time (Fig. S1). Soluble $\text{PO}_4\text{-P}$ did not increase under CaSiO_3 (Fig. 4). It decreased sharply in both minerals at both time points. At 96 h, 2.5 mM CaSiO_3 reduced $\text{PO}_4\text{-P}$ from 0.374 to 0.078 mg L^{-1} in HA (– 79%; $P = 0.0022$) and from 1.94 to 0.196 mg L^{-1} in FePO_4 (– 90%; $P = 1.7 \times 10^{-6}$), and at 189 h the reductions reached – 98% in HA and – 97% in FePO_4 (both $P < 0.001$). CaSiO_3 therefore raised pH and ionic strength while reducing measured soluble $\text{PO}_4\text{-P}$, rather than releasing phosphate into solution.

3.6 The broader ionome supported P-source-specific effects

The broader shoot ionome supported P-source-specific CaSiO_3 effects (Table S5; Fig. S2; summarized in Table 1). HA showed coordinated CaSiO_3 -associated increases across P, Ca, Fe, K, Mg, Mn, Na, Zn and S, in the source that was biomass-limiting without CaSiO_3 . This broad increase tracked the large HA biomass gain. FePO_4 instead showed a narrower Fe and Mn response against its high-biomass, high-P baseline, without a matching biomass increase. KH_2PO_4 showed an Fe increase and a Zn decrease, whereas its large apparent P and Mn percentage changes were not robust given the high NoSi variance. NoP showed several concentration shifts but little growth response. The acid-recovered Si values are reported in the supplementary ionome table as an operational measurement, but were not used to infer total Si uptake or mechanism.

Table 1

P-source baseline status and main measured CaSiO_3 effect by source. Full ANOVA, planned-contrast and element-by-element ionome tables are provided as supplementary source tables.

P source	NoSi baseline	Main measured CaSiO_3 effect
KH_2PO_4	Soluble-P control; biomass and shoot P above NoP	Increased shoot biomass and root length, surface area and volume; no root-mass increase
Hydroxyapatite	Limiting P source; biomass near NoP	Increased shoot biomass, root biomass, estimated shoot P content and average root diameter
FePO_4	High-baseline P source; biomass and shoot P already high	Increased shoot Fe and Mn; weak, non-significant biomass and root-length trends
NoP	No added P; low biomass and shoot P	Small, mostly non-significant biomass and root responses with several concentration shifts

4 Discussion

4.1 A single calcium-silicate amendment produced P-source-dependent responses

The central result is that CaSiO_3 changed wheat performance differently according to the chemical context of P supply, rather than producing a uniform stimulation (Fig. 1). HA showed the clearest growth and P uptake response, KH_2PO_4 showed shoot-growth and root-architecture responses under soluble P, FePO_4 showed strong Fe and Mn responses on an already high-P baseline, and NoP showed concentration shifts without meaningful growth (Table 1). These data support P-source-dependent calcium-silicate response modes rather than one generic Si mechanism, consistent with the broader Si-P literature. The high FePO_4 baseline is consistent with the established ability of wheat to take up P from sparingly soluble iron phosphate [21], and a related experiment confirmed this contrast directly, with wheat acquiring P from iron phosphate but not from hydroxyapatite while chickpea showed the reverse (Tiwari et al., in preparation). The present factorial adds a controlled demonstration that the same amendment does not have the same biological outcome when P is soluble, absent, or bound as calcium or iron phosphate. The principal CaSiO_3 -by-P-source response directions reproduced in an independent earlier run (Table S1), supporting their robustness.

4.2 The abiotic assay points to a plant- and rhizosphere-mediated hydroxyapatite response

The abiotic assay was designed to test whether calcium-silicate chemistry alone could account for the HA response, and it returned a clear answer (Fig. 4). CaSiO_3 raised pH and EC strongly (Fig. S1), confirming that the amendment changed solution chemistry, but soluble PO_4 -P fell by 79 to 98% rather than rising. Calcium silicate therefore did not release phosphate from HA or FePO_4 under these

conditions. If anything, it locked phosphate up, consistent with precipitation or sorption at high pH and ionic strength [1]. The HA plants, by contrast, grew larger and accumulated more shoot P. The growth and P-accumulation response on HA cannot be explained by abiotic dissolution of the mineral in bulk solution, and instead points to processes at the root surface and rhizosphere rather than in the bulk medium. The soluble-P positive control reinforces this conclusion. Under KH_2PO_4 , where there is no sparingly soluble mineral to dissolve, CaSiO_3 still increased shoot biomass and enlarged the root system, so a plant-growth component operates independently of any mineral-P chemistry. The HA response went beyond this generic growth component, because CaSiO_3 there also increased root biomass and root diameter, neither of which changed under soluble P. This contrasts with acid-soil work in which Si raised rhizosphere-available P [15]. The opposite directions, in an acid soil and in the present alkaline, high-ionic-strength assay, indicate that the soil-chemical effect is itself pH- and source-dependent, which reinforces rather than weakens the P-source-dependence thesis. In a related intercrop experiment a chickpea neighbour unlocked hydroxyapatite-bound P for wheat, plausibly through rhizosphere acidification and carboxylate release (Tiwari et al., in preparation). The present amendment reached the same outcome by raising pH rather than dissolving the mineral, so access to calcium-bound P for wheat is, by inference, a root- and rhizosphere-mediated outcome reachable by more than one route.

4.3 Root architecture is the strongest plant route to the hydroxyapatite response

Root architecture provides the most direct plant evidence for how CaSiO_3 improved HA-grown wheat, although the root data cannot by themselves prove increased phosphate influx (Fig. 3; within-source contrasts with Benjamini-Hochberg q values in Table S6). The CaSiO_3 root response was P-source-specific. On HA, CaSiO_3 increased root biomass, surface area, volume and average diameter, producing a larger and coarser root system under this limiting P source, whereas KH_2PO_4 produced a larger scanned root system without a matching increase in root dry mass. A larger and more developed root system explores more sand and presents more absorbing surface to sparingly soluble P, which can raise harvested P even when bulk solubility does not change. This interpretation fits the role of root morphology in wheat P acquisition, because wheat under low P relies strongly on maintaining root biomass and length, whereas rhizosphere acidification and acid-phosphatase activity do not increase under low P [7], and Si stimulates the wheat root system [11]. The present hydroxyapatite response was led by increased root diameter, whereas Si increased wheat root length but not diameter both under drought [11] and, on the same cultivar under adequate P (Karwa and Halpern, under review). The diameter increase here is therefore a P-source-specific change in root form rather than a generic Si effect on root length. The pattern is also consistent with wheat work in which root length and surface area respond to P supply [22], and with species comparisons showing that access to aluminium, iron and calcium phosphates cannot be explained by carboxylate release alone [5]. Other Si-P studies show that this root and rhizosphere layer can include processes not measured here. In rice, Si was associated with greater root organic-acid release, shifts in P-solubilizing microbial groups and upregulation of *OsPT2*, *OsPT4* and *OsPT8* [23], whereas wheat rhizosphere studies link Si to pH, organic carbon and P bioavailability [24]. Rhizosphere-resolved imaging in rice likewise detected Si-associated root-

architecture, phosphatase-hotspot and P-depletion patterns that bulk measurements did not capture [25]. The most defensible interpretation is therefore a root-driven and rhizosphere-driven improvement in access to HA-bound P. The amendment may also act through exudation, rhizosphere pH or microbial processing rather than through root architecture alone.

4.4 The hydroxyapatite ionome rise tracks growth, whereas the FePO_4 metal response is element-specific

The shoot ionome separates a growth-driven response from an element-specific one (Fig. 2). On HA, CaSiO_3 raised P, Ca, K, Mg, Fe, Mn, Na, Zn and S together, in step with the large biomass gain (Table S5; Fig. S2). The broad HA ionome rise is therefore most parsimoniously read as a larger plant taking up more of many elements, rather than as element-specific transport. On FePO_4 , by contrast, biomass barely changed, but shoot Fe and Mn rose strongly, which marks an element-specific response rather than a size effect. This pattern is consistent with Si interacting with Fe availability or plant metal-homeostasis pathways, although those studies concern Si rescuing Fe under deficiency, whereas here shoot Fe rose from a sufficient baseline [26, 27]. Classic rice work and reviews often describe Si benefits under P imbalance as reduced Fe or Mn accumulation [18, 19], whereas CaSiO_3 here increased shoot Fe and Mn, especially under FePO_4 . Those systems differ in species, Si form and baseline P status, so the contrast reflects a different context rather than a contradiction. The rise in plant Fe and Mn cannot come from bulk solution, because high pH due to added CaSiO_3 would precipitate Fe, and would be expected to lower Mn availability, so the FePO_4 metal response points to a root-zone or plant-physiological process rather than bulk chemistry. The abiotic assay measured soluble $\text{PO}_4\text{-P}$ rather than Fe or Mn, so this inference rests on the expectation that high pH lowers Fe and Mn solubility.

5 Conclusions

Calcium silicate changed wheat performance in ways that depended on P-source chemistry. The clearest effect was on hydroxyapatite: without CaSiO_3 wheat grew little on this source, whereas with CaSiO_3 it grew, with coordinated increases in biomass, estimated shoot P content and root-system size. Hydroxyapatite was the only added phosphorus in that treatment, so the additional phosphorus was acquired from the mineral itself, and the amendment enabled wheat to use a phosphorus source that was otherwise poorly available. KH_2PO_4 showed that the amendment can stimulate shoot growth and root architecture even when P is soluble, and FePO_4 supported high biomass and shoot P status without CaSiO_3 but showed strongly increased Fe and Mn accumulation with it. The abiotic assay showed that CaSiO_3 decreased rather than increased bulk soluble $\text{PO}_4\text{-P}$, so the hydroxyapatite growth and P-accumulation response cannot be a bulk-dissolution effect and instead points to a plant- and rhizosphere-mediated process. Calcium was balanced with CaCl_2 in the NoSi treatments, so the responses are also unlikely to reflect simple calcium addition. The results are consistent with multiple P-source-dependent, plant- and rhizosphere-mediated response modes to a calcium-silicate amendment,

and pH-buffered, rhizosphere-resolved designs will be needed to identify the dominant plant process in each P-source context.

Declarations

Competing interests

The authors declare no competing interests.

Ethics approval

Not applicable. The study did not involve human participants or animals.

Consent to participate

Not applicable.

Consent for publication

Not applicable.

Overlapping use of data

A subset of these data, the no-silicon shoot-biomass means for hydroxyapatite, FePO_4 and the no-added-P control, is also used in a related study of wheat-chickpea phosphorus facilitation (Tiwari et al., in preparation), where the present experiment serves as an independent second-cultivar test that wheat does not access hydroxyapatite without amendment. The two papers report non-overlapping analyses of the same experiment. The full silicon $\times$ P-source dataset and all silicon comparisons are reported only here. Both papers cross-cite this overlap.

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Author Contribution

S.K.: investigation, methodology, data curation, and writing (review and editing). M.H.: conceptualization, supervision, formal analysis, software, visualization, and writing (original draft, and review and editing). Both authors read and approved the final manuscript.

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Data Availability

The data generated and analysed in this study are openly available in Zenodo at <https://doi.org/10.5281/zenodo.21215456>. The curated deposit contains the cleaned datasets, analysis scripts, statistical outputs, and figure source data.

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Figures

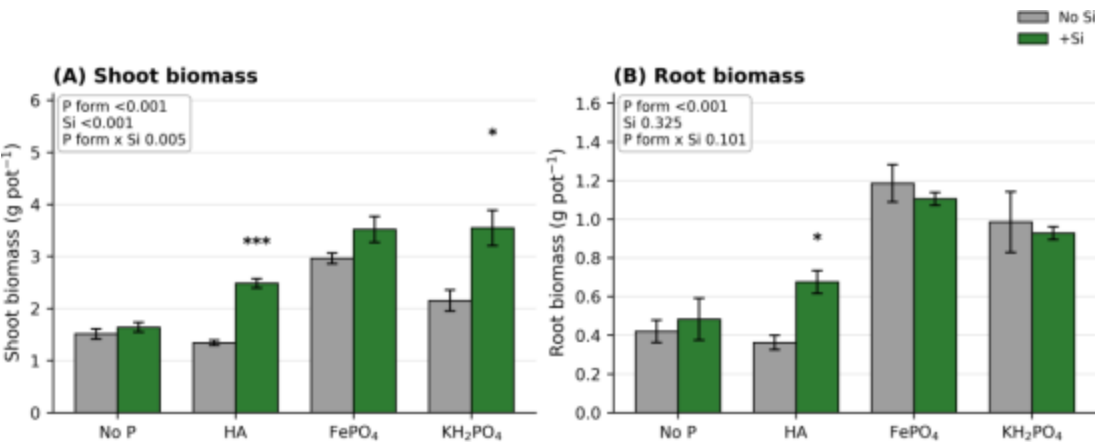


Figure 1

Wheat biomass by P source and calcium-silicate treatment. Run 2 shoot biomass (A) and root biomass (B), both g pot⁻¹, for no added P (NoP), hydroxyapatite (HA), FePO₄ or KH₂PO₄. Bars are means ± SE; grey = no CaSiO₃ (NoSi), green = CaSiO₃ (Si). Asterisks above +Si bars denote planned within-source NoSi versus CaSiO₃ contrasts after Holm adjustment within each panel (**P* < 0.05, ***P* < 0.01, ****P* < 0.001); absence of an asterisk indicates *P* ≥ 0.05. Insets report ANOVA *P* values for P source, CaSiO₃ and their interaction. n per cell in Table S2.

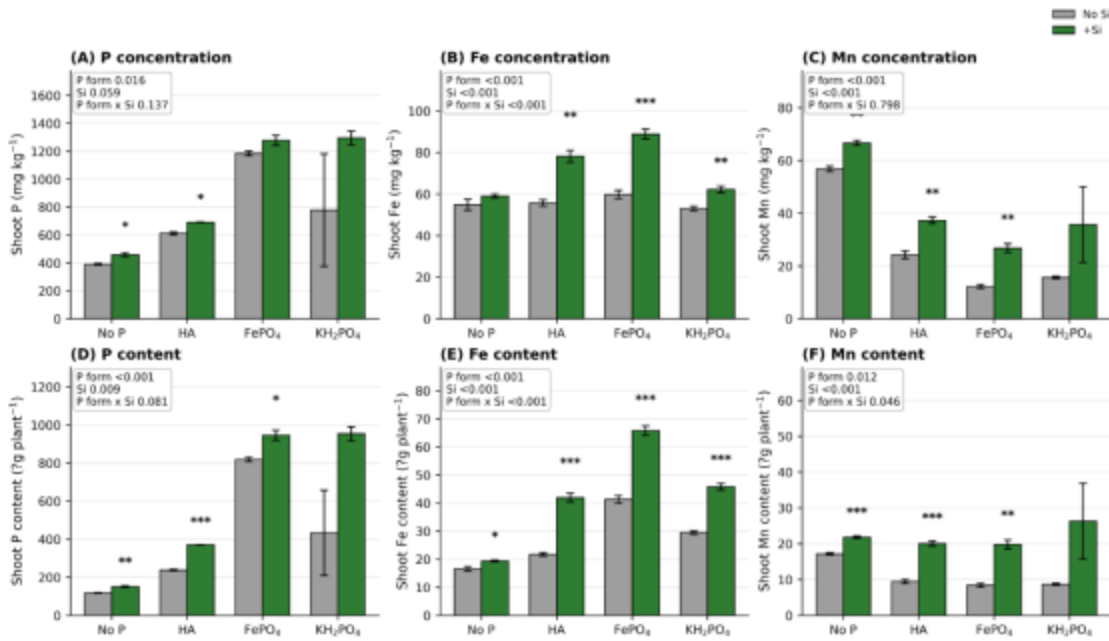


Figure 2

Shoot P, Fe and Mn concentration and estimated content by P source and calcium-silicate treatment. Top row, shoot concentration (mg kg⁻¹) of P (A), Fe (B) and Mn (C); bottom row, estimated shoot content (µg plant⁻¹) of P (D), Fe (E) and Mn (F), where content = concentration × treatment-cell mean shoot dry mass per plant. Bars are means ± SE; grey = NoSi, green = Si (CaSiO₃); P-source codes as in Fig. 1. Asterisks above +Si bars denote planned within-source NoSi versus CaSiO₃ contrasts after Holm adjustment within each panel (**P* < 0.05, ***P* < 0.01, ****P* < 0.001); absence of an asterisk indicates *P* ≥ 0.05. Insets report ANOVA *P* values, with transforms listed in Table S2 and means plotted on the original scale. n per cell in Table S2.

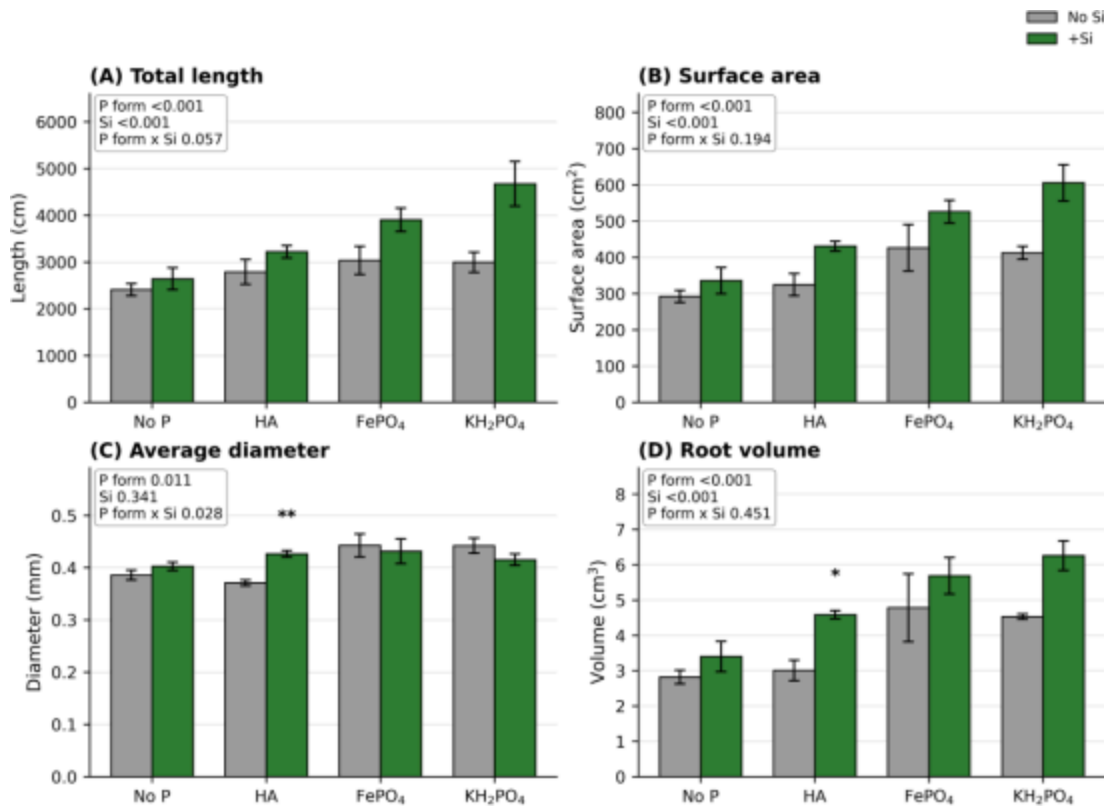


Figure 3

Root architecture by P source and calcium-silicate treatment. Day-30 WinRHIZO total root length (A, cm), surface area (B, cm²), average diameter (C, mm) and root volume (D, cm³). Bars are means $\pm$ SE; grey = NoSi, green = Si (CaSiO₃); P-source codes as in Fig. 1. Asterisks above +Si bars denote planned within-source NoSi versus CaSiO₃ contrasts after Holm adjustment within each panel (* P < 0.05, ** P < 0.01, *** P < 0.001); absence of an asterisk indicates $P \geq 0.05$. Insets report ANOVA P values. n per cell in Table S2.

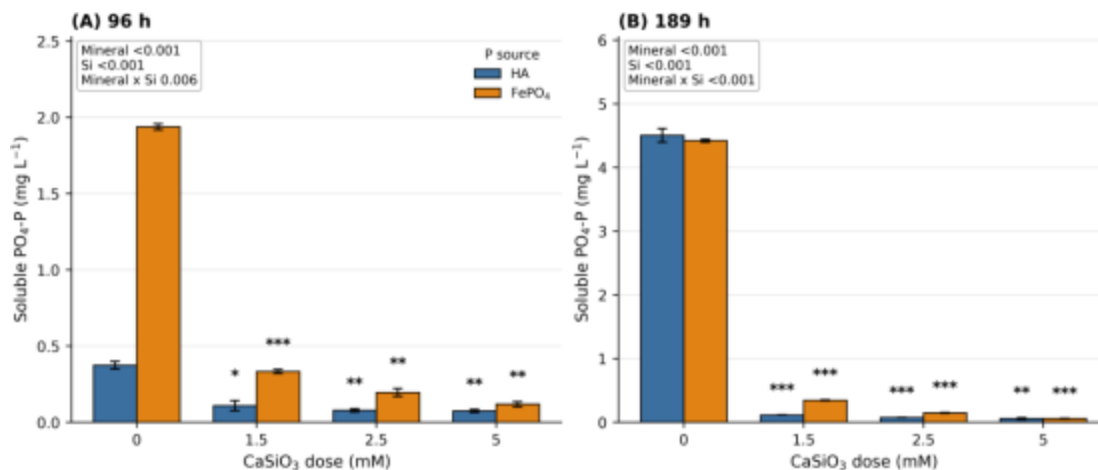


Figure 4

Abiotic soluble $\text{PO}_4\text{-P}$ in sand-mineral mixtures. Soluble $\text{PO}_4\text{-P}$ (mg L^{-1}) after 96 h (A) and 189 h (B) in shaken sand mixtures containing HA or FePO_4 with 0, 1.5, 2.5 or 5.0 mM CaSiO_3 . Bars are means $\pm$ SE; blue = HA, orange = FePO_4 . Asterisks above CaSiO_3 -dose bars denote planned comparisons with 0 mM CaSiO_3 within the same mineral and time point after Holm adjustment within each mineral-time family (* $P < 0.05$, ** $P < 0.01$, * $P < 0.001$). Insets report ANOVA P values for mineral, CaSiO_3 dose and their interaction, based on $\log_{10}$ -transformed values. n per cell in Table S2.**

Supplementary Files

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