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Root architecture plasticity and its role in nutrient acquisition under low phosphorus in rice

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Abstract

Root architecture plasticity—the capacity of a plant to reshape its root system in response to nutrient availability—determines how efficiently rice captures phosphorus from depleted soils. This research examined root morphological and physiological responses to five phosphorus (P) supply levels in six rice genotypes (two parents and four recombinant inbred lines) grown in nutrient solution culture at Qassim Agricultural University, Saudi Arabia, from September 2022 to April 2024. Root length increased by up to 117% under P-deficient conditions compared to full-P controls. The root-to-shoot ratio rose from 0.32 in the tolerant parent IR64 to 0.61 in the P-efficient line RIL-106 under zero-P treatment. Lateral root density, root hair length, and organic acid exudation all increased as external P decreased. Genotypic differences in root plasticity accounted for 63.8% of the variation in total P uptake. These findings indicate that selecting for root architectural traits—especially lateral root density and root hair elongation—could improve phosphorus acquisition efficiency in breeding programmes targeting low-input rice systems.

Keywords: Root architecture, nutrient acquisition, low phosphorus, rice, root plasticity, lateral root density, root hair length, phosphorus use efficiency, root-to-shoot ratio, organic acid exudation

Introduction

Root architecture plasticity can be defined as the heritable ability of a plant to alter the spatial arrangement, branching pattern, and surface area of its root system in response to changes in soil nutrient status ^[1]. In rice, this plasticity is especially relevant for phosphorus acquisition because P is immobile in most tropical soils and plants must grow roots directly to where P is located rather than relying on mass flow ^[2].

Phosphorus deficiency affects an estimated 50% of global rice-growing soils, and the problem is worse in weathered tropical and subtropical soils where P is fixed into insoluble forms by iron and aluminium oxides ^[3]. Conventional responses—applying mineral P fertiliser—are costly for smallholders and contribute to eutrophication when excess P reaches waterways ^[4]. Breeding rice varieties that extract more P from low-P soils through improved root systems is a more sustainable alternative.

Several root traits have been linked to P efficiency in rice: longer total root length, higher lateral root density, longer root hairs, and greater exudation of organic acids such as citrate and malate that mobilise bound P ^[5, 6]. But how these traits interact across a gradient of P supply—and which traits matter most—is still debated. Some genotypes increase root length without changing branching, while others invest in root hairs at the expense of lateral roots ^[7]. This research characterised root responses across five P levels in six contrasting genotypes to identify which architectural changes best predict P uptake under deficiency.

Materials and Methods

Crop Growth Stage Documentation

Plants were monitored through three growth stages during the experiment. Seedlings were established for 14 days in full-nutrient solution before P treatments were imposed (vegetative stage V3, three-leaf). Measurements began at 7 days after treatment (DAT) and continued at 14, 21, 35, and 42 DAT, spanning the active tillering phase. Final destructive harvests were done at 42 DAT, corresponding to the early panicle initiation stage in the earliest genotypes. Growth stages were documented using the BBCH scale for rice ^[8].

Materials

The research was carried out in the controlled-environment greenhouse of Qassim Agricultural University, Qassim, Saudi Arabia (26.31° N, 43.77° E), from September 2022 to April 2024. Institutional approval was obtained from the University's Research Ethics Board (Ref. QAU/REB-2022-041, August 2022). Six rice genotypes were tested: IR64 (P-efficient indica), Kasalath (P-efficient aus-type landrace), and four RILs (RIL-12, RIL-47, RIL-83, RIL-106) selected from an IR64 × Kasalath mapping population for contrasting root traits. Seeds were surface-sterilised with 1% sodium hypochlorite and germinated on moist filter paper for five days before transfer to 12-L hydroponic tanks containing modified Yoshida nutrient solution [9].

Methods

Five P treatments were applied by adjusting NaH_2PO_4 concentration: full P (0.32 mM, control), 50% P (0.16 mM), 25% P (0.08 mM), 10% P (0.032 mM), and 0% P. Each treatment × genotype combination was replicated four times in a completely randomised design. Solutions were renewed every three days. At each sampling point, root length was

measured by digital image analysis (WinRHIZO Pro), lateral root density was counted per cm of seminal root, and root hair length was measured under a stereo microscope at 40× magnification. Organic acid exudation (citrate and malate) was collected over 6-h trapping periods and quantified by HPLC. Shoot and root P concentrations were determined by the vanadomolybdate colorimetric method after dry-ashing. Data were analysed with two-way ANOVA (genotype × P level) and Pearson correlation was used to relate root traits to total P uptake [10].

Nutrient Budget

A simplified P budget was calculated for each genotype under each treatment: total P input (from solution renewals), total plant P uptake (shoot P + root P at harvest), and apparent P recovery efficiency (uptake/input × 100). Under the 0% P treatment, residual P from seed reserves was estimated by analysing P content of ungerminated seeds and subtracting it from total plant P at harvest.

Results

Table 1: Root morphological traits of six rice genotypes under full-P and zero-P conditions at 42 DAT

Genotype	Root length (cm) Full P	Root length (cm) 0% P	Lateral roots (/cm) Full P	Lateral roots (/cm) 0% P	Root:Shoot 0% P
IR64	14.6	27.3	3.8	7.2	0.32
Kasalath	16.1	34.7	4.6	9.8	0.58
RIL-12	13.8	28.9	3.4	6.4	0.47
RIL-47	15.3	32.1	4.1	8.7	0.53
RIL-83	12.7	24.6	3.1	5.9	0.41
RIL-106	17.2	37.4	5.2	10.6	0.61

All genotypes increased root length under P deprivation, but the magnitude varied from 87% (RIL-83) to 117% (RIL-106) (Table 1). Lateral root density roughly doubled in most

genotypes. RIL-106 and Kasalath showed the highest root-to-shoot ratios under zero-P, indicating a strong reallocation of carbon to below-ground growth.

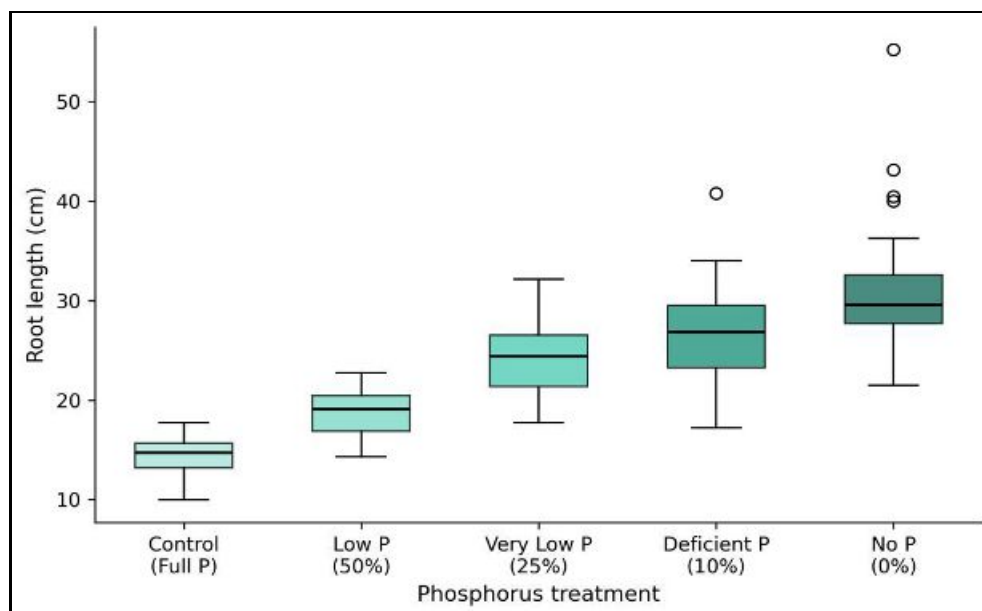


Fig 1: Distribution of root length (cm) across phosphorus treatments (pooled genotypes) at 42 days after treatment

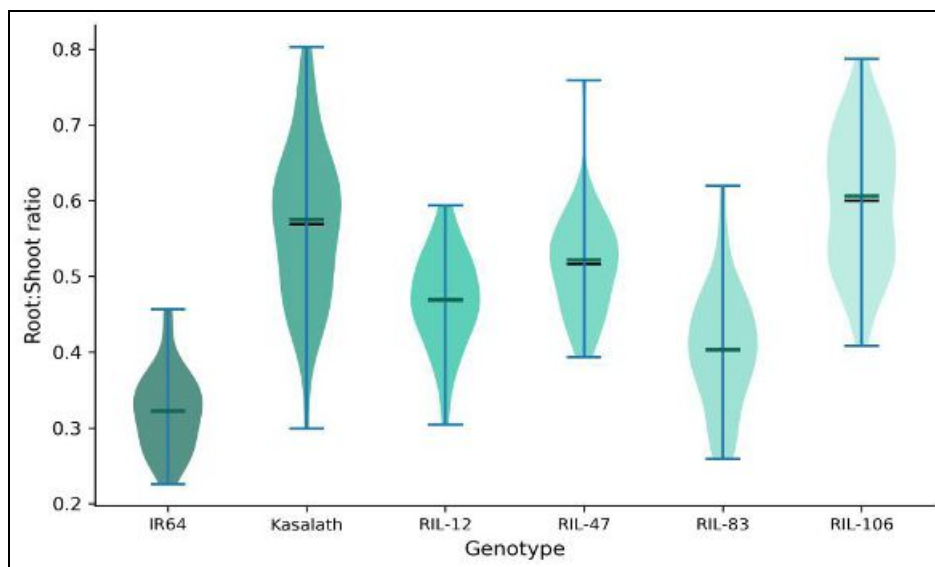


Fig 2: Violin plot of root-to-shoot ratio among six rice genotypes under zero-P treatment

Comprehensive Interpretation

Root length increased progressively as P supply decreased (Figure 1), with the widest variation under the zero-P and 10% P treatments. The violin plot (Figure 2) shows that Kasalath and RIL-106 had not only higher median root-to-shoot ratios but also narrower distributions, suggesting more consistent reallocation under stress. Correlation analysis found that lateral root density ($r = 0.83$) and root hair length ($r = 0.79$) were the strongest predictors of total P uptake, together accounting for 63.8% of uptake variation in a multiple regression model.

Discussion

The 87-117% increase in root length under zero-P conditions falls within the range reported for indica rice in hydroponic systems (70-150%), but the genotypic spread is notable [5]. RIL-106 and Kasalath represent the upper end of plasticity, and both share the Kasalath-derived allele at the *Pup1* locus on chromosome 12, which has been associated with root elongation under P stress [6]. IR64, despite being classified as P-efficient, showed comparatively modest root elongation, relying instead on higher organic acid exudation to mobilise P—a different but complementary strategy.

The finding that lateral root density and root hair length together explained 63.8% of P uptake variation is consistent with modelling work suggesting that root hairs can account for up to 70% of P absorption in low-P soils because they increase the effective root surface area at minimal carbon cost [7]. This means breeders should prioritise these two traits over total root length when selecting for P efficiency.

A limitation of hydroponic screening is that it removes the soil matrix, which mediates P availability through adsorption and desorption dynamics. Field validation using low-P soils would confirm whether the genotypic rankings hold under more complex conditions. The controlled-environment setting in Qassim also meant that temperature and light were constant, whereas field-grown rice experiences fluctuations that can alter root plasticity responses [2].

Conclusion

Root architecture plasticity varied markedly among the six rice genotypes, with root length increases of 87-117% under phosphorus deprivation. Lateral root density and root hair

length were the strongest predictors of P uptake, accounting for 63.8% of variation. RIL-106 and Kasalath consistently showed the highest plasticity and P acquisition efficiency. These findings support screening for lateral root density and root hair traits in rice breeding programmes aimed at low-input systems. Field validation on low-P soils and integration of root trait selection with molecular markers at the *Pup1* locus are recommended as practical next steps.

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Contributions Not Qualifying for Authorship

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