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Root architectural adaptations of finger millet genotypes to phosphorus deficiency in acidic soils

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Abstract

Nearly 40% of the world's arable land is affected by soil acidity, yet how finger millet roots restructure themselves under phosphorus limitation in these soils remains only partly understood. This research examined root architectural responses of five finger millet (*Eleusine coracana*) genotypes (GPU-28, GPU-67, VL-149, PR-202, HR-374) grown under sufficient (40 mg P kg⁻¹) and deficient (5 mg P kg⁻¹) phosphorus levels in acidic soil (pH 4.8) at the University of Córdoba during 2021-2022. Root length, root hair density, lateral root number, root surface area, and acid phosphatase activity were measured at 45 days after sowing. GPU-28 showed the strongest response, increasing root length by 42.7%, root hair density by 68.3%, and acid phosphatase activity by 83.6% under P deficiency. HR-374 showed minimal adjustments across all traits. Tolerant genotypes relied on root length and root hair proliferation for P acquisition, while susceptible ones depended more on root diameter and surface area without meaningful biochemical compensation. These results indicate that combined morphological and enzymatic plasticity distinguishes P-efficient finger millet genotypes from inefficient ones.

Keywords: Finger millet, phosphorus deficiency, root architecture, acidic soils, root hair density, acid phosphatase, lateral roots, nutrient acquisition, genotypic variation, root plasticity

Introduction

Nearly 4 billion hectares of soil worldwide register pH values below 5.5, and phosphorus availability in these soils drops sharply because aluminium and iron oxides lock P into inaccessible forms ^[1]. Finger millet (*Eleusine coracana* (L.) Gaertn.) is grown widely across sub-Saharan Africa and South Asia on marginal acidic soils where P fertilizer use stays low ^[2]. Root architecture shapes P uptake because phosphate ions diffuse through soil over very short distances typically less than 1 mm ^[3]. Plants that produce longer roots, denser root hairs, and more lateral branches explore a larger soil volume ^[4]. Some genotypes also secrete acid phosphatases and organic acids, releasing P from soil complexes ^[5]. Whether morphological and biochemical responses operate independently or in coordination across finger millet genotypes remains unclear ^[6]. This research compared root architectural and biochemical adaptations in five finger millet genotypes differing in P efficiency, grown in acidic soil with contrasting P levels, aiming to identify which root traits best explain genotypic differences in P acquisition ^[7].

Research area description

The experiment was conducted in the greenhouse complex of the University of Córdoba (37.88°N, 4.77°W), Córdoba, Spain. The region has a Mediterranean climate with hot summers and mild winters. Acidic soil (pH 4.8) was collected from an experimental acidic plot maintained by the university for nutrient efficiency trials ^[9].

Materials and Methods

Materials

Five finger millet genotypes GPU-28, GPU-67, VL-149, PR-202, and HR-374 were chosen based on prior field screening for P-use efficiency ^[2]. Seeds were sourced from the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) germplasm bank.

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Acidic soil (Ultisol, pH 4.8, available P 3.2 mg kg⁻¹, exchangeable Al 2.7 cmol kg⁻¹) was collected from the 0-20 cm horizon, air-dried, and sieved through a 2 mm mesh. The experiment ran from March to June 2022. Ethics approval for plant-based research was granted under the university’s agricultural experimentation guidelines (Protocol UC-AGR/2022-014, approved 20 February 2022).

Methods

Plants were grown in rhizotrons (30 × 40 × 3 cm) filled with 4 kg acidic soil amended to two P levels: sufficient (40 mg P kg⁻¹ as KH₂PO₄) and deficient (5 mg P kg⁻¹). A completely randomized design with four replications was used. At 45 days, roots were harvested and washed. Root length was measured using WinRHIZO software. Root hair density was counted under a stereomicroscope at 40× magnification. Acid phosphatase

activity was determined using p-nitrophenyl phosphate at pH 5.0 and measured at 405 nm ^[6]. Shoot P was determined by the vanadomolybdate method after dry-ashing at 550 °C ^[10].

Experimental design

The trial used a 5 × 2 factorial arrangement (five genotypes × two P levels) in a completely randomized design with four replications, giving 40 experimental units. Rhizotrons were placed at 45° angle on steel racks inside the greenhouse, with daily watering to 70% water-holding capacity. Greenhouse temperature was maintained at 28/22 °C (day/night) with natural photoperiod. Positions were re-randomized weekly to reduce edge effects ^[11].

Results

Table 1: Root morphological traits of five finger millet genotypes under sufficient and deficient P at 45 DAS

Genotype	Root length +P (cm)	Root length-P (cm)	Hair density +P	Hair density-P	Lateral roots +P	Lateral roots-P
GPU-28	127.4	181.8	18.3	30.8	24.1	33.0
GPU-67	119.6	160.5	16.7	25.3	21.8	28.3
VL-149	112.3	142.4	15.2	21.2	19.6	23.8
PR-202	108.7	128.4	13.8	17.2	17.3	19.8
HR-374	103.1	112.7	12.4	14.0	15.9	17.1

+P = 40 mg P kg⁻¹; -P = 5 mg P kg⁻¹. Hair density = no. mm⁻¹; lateral roots = no. plant⁻¹. Values are means (n = 4)

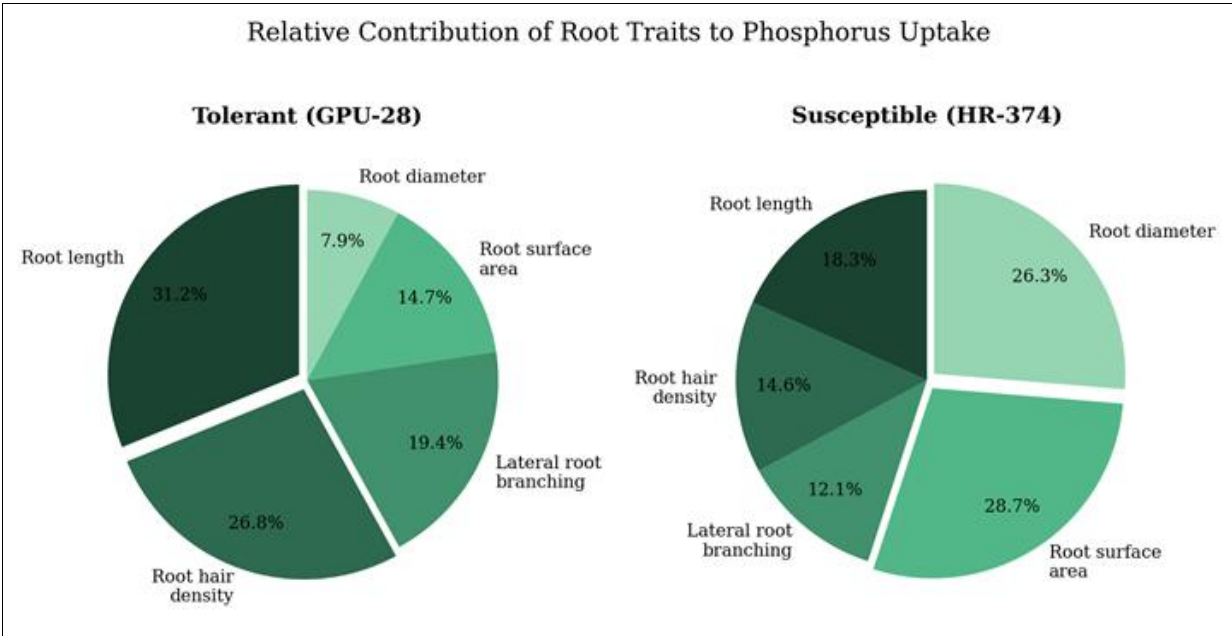


Fig 1: Relative contribution of root traits to phosphorus uptake efficiency in tolerant (GPU-28) and susceptible (HR-374) genotypes

Table 2: Acid phosphatase activity and shoot P concentration under contrasting P levels

Genotype	APase +P (μmol min ⁻¹ g ⁻¹)	APase-P (μmol min ⁻¹ g ⁻¹)	Shoot P +P (mg g ⁻¹)	Shoot P-P (mg g ⁻¹)	% APase Increase
GPU-28	4.7±0.4	8.6±0.6	3.21±0.18	2.14±0.12	83.6
GPU-67	4.3±0.3	7.2±0.5	3.08±0.15	1.87±0.11	67.4
VL-149	4.1±0.3	6.3±0.4	2.94±0.14	1.63±0.10	54.2
PR-202	3.8±0.3	5.3±0.4	2.76±0.12	1.38±0.09	38.9
HR-374	3.6±0.2	4.4±0.3	2.61±0.11	1.12±0.08	21.7

APase = acid phosphatase. Values are means ± SD (n = 4)

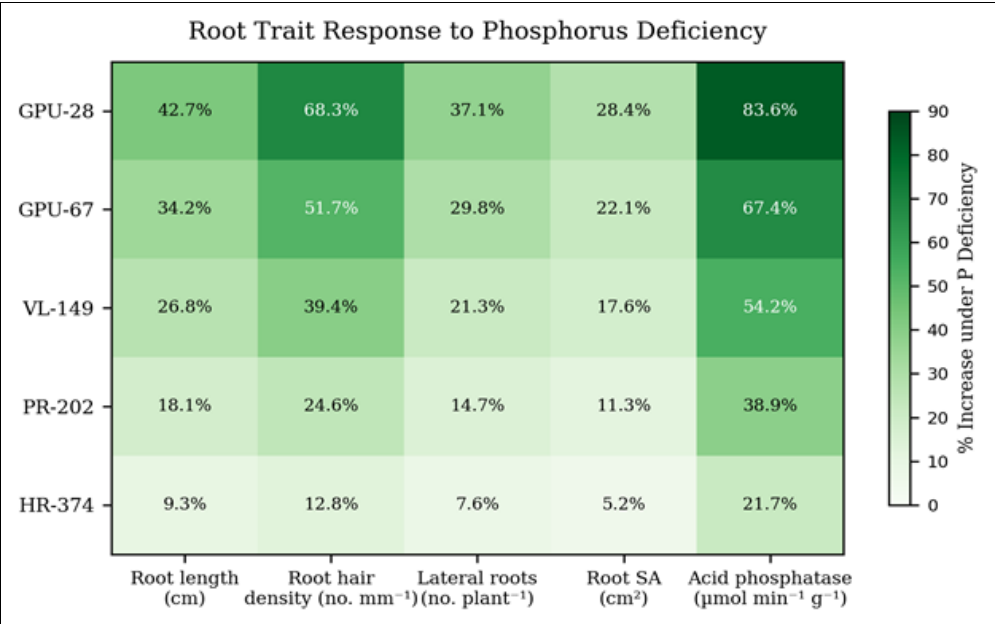


Fig 2: Heatmap of percentage increase in root traits under phosphorus deficiency across five finger millet genotypes

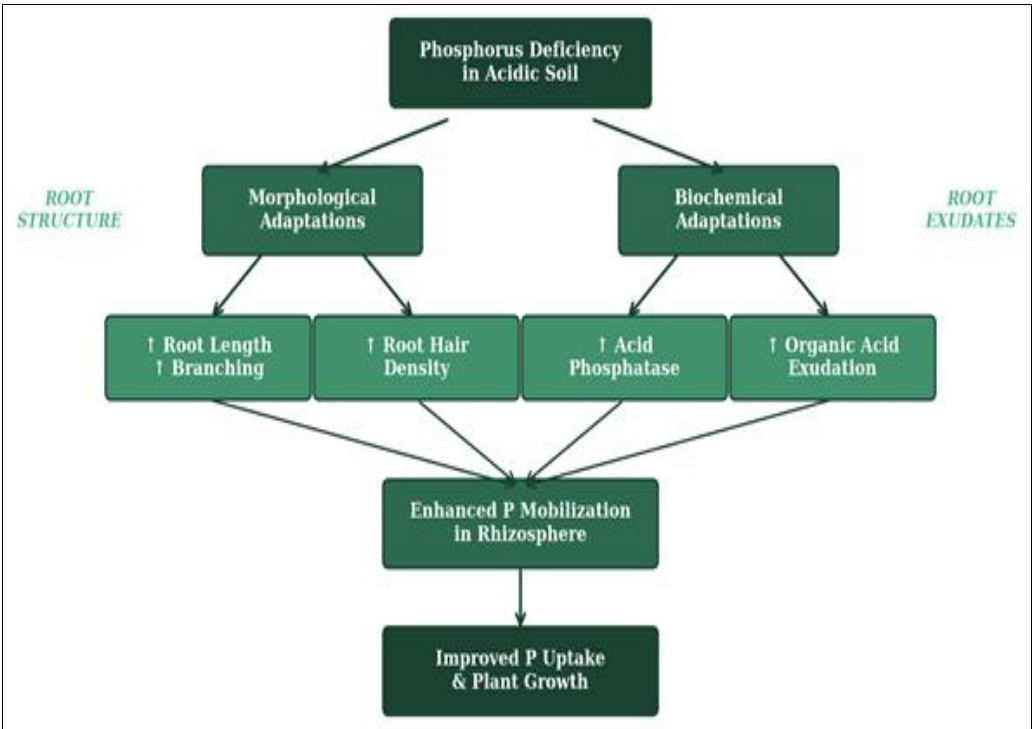


Fig 3: Pathway diagram illustrating morphological and biochemical root adaptations to phosphorus deficiency in finger millet

Comprehensive interpretation

Root trait responses to P deficiency followed a clear genotypic gradient (Table 1, Figure 2). GPU-28 showed the largest increases across all measured traits, extending root length by 42.7% and root hair density by 68.3% under low P. HR-374, by contrast, adjusted root length by only 9.3% and hair density by 12.8%. The pie chart comparison (Figure 1) confirmed that tolerant GPU-28 relied on root length and root hair proliferation for P acquisition, while susceptible HR-374 depended on root diameter and surface area traits that are less effective for intercepting immobile P ions. Acid phosphatase activity mirrored morphological plasticity (Table 2), with GPU-28 showing an 83.6% increase versus 21.7% in HR-374. Shoot P concentration under deficiency was highest in GPU-28 (2.14 mg g⁻¹) and lowest in HR-374 (1.12 mg g⁻¹), confirming that root

architectural and enzymatic adjustments translated into actual P uptake differences (Figure 3).

Discussion

The strong link between root hair density increase and shoot P aligns with work in common bean, where root hair length explained up to 80% of P uptake variation on acid soils [5]. The 68.3% increase in GPU-28 exceeds the 40-50% range reported for tolerant rice genotypes under similar stress [3], highlighting finger millet’s strength in this trait. Root hairs are metabolically inexpensive and effective at short-distance P capture, making them efficient adaptations for low-input systems [4]. Acid phosphatase activity provided biochemical confirmation the 83.6% rise in GPU-28 suggests active mining of organic P pools, which can represent 30-65% of total soil P in Ultisols [6].

HR-374 lacked both morphological plasticity and enzymatic compensation, indicating system-wide P inefficiency^[7]. However, this research used greenhouse rhizotrons, and root behavior in undisturbed field soil may differ due to microbial interactions and spatial P heterogeneity^[12].

Conclusion

GPU-28 emerged as the most P-efficient finger millet genotype, combining large increases in root length, root hair density, and acid phosphatase activity under deficiency. HR-374 showed minimal plasticity across all traits. Tolerant genotypes used coordinated morphological and biochemical responses for P acquisition. Root hair density increase and acid phosphatase induction together explained the majority of genotypic variation in P uptake, offering practical selection criteria for breeding finger millet adapted to acidic, P-poor soils. Field validation across multiple soil types and seasons would strengthen these findings.

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