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Root architecture modifications in pigeonpea for improved water extraction from deep soil layers

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Abstract

A growing body of evidence suggests that the next leap in dryland crop productivity will come from below ground rather than above it. This research compared root architecture and deep-water extraction in three pigeonpea (*Cajanus cajan*) genotypes—ICPL 87119 (standard), ICP 7035 (deep-rooted), and ICPL 332 (compact)—grown in 1.5 m deep rhizotrons at the University of Hohenheim, Stuttgart, Germany, over two seasons (2022-2023). ICP 7035 maintained root length density of 1.3 cm cm^{-3} at 105 cm depth, four-fold higher than ICPL 332 (0.1 cm cm^{-3}). Under terminal drought, ICP 7035 extracted 68% more water from the 60-120 cm zone and yielded 34% more grain than the compact type. Steep root angle ($\geq 60^\circ$) and aerenchyma formation were identified as the key traits enabling deep-root function.

Keywords: Pigeonpea, root architecture, deep rooting, water extraction, rhizotron, *Cajanus cajan*, drought tolerance, root length density, aerenchyma, genotype

Introduction

A trend is building across dryland crop breeding: look deeper. While above-ground traits like leaf rolling and early maturity have been selected for decades, root system architecture—particularly the ability to reach moisture below 60 cm—remains largely unexploited in pigeonpea improvement programmes ^[1, 2].

Pigeonpea is a key pulse in semi-arid tropics, grown on roughly 5.5 million hectares worldwide, mostly under rain-fed conditions where terminal drought during pod filling is the single largest yield constraint ^[3, 4]. Genotypes with steep root angles and high root length density at depth can access residual moisture that shallow-rooted types miss ^[5]. This research aimed to: (i) characterise root architecture differences among three genotypes to 120 cm depth, (ii) quantify water extraction profiles under terminal drought, and (iii) identify the morphological traits most strongly linked to deep-water uptake.

Materials and Methods

Research Area

Experiments were conducted in the root phenotyping facility at the University of Hohenheim (48°42' N, 9°11' E), Stuttgart, Germany, during 2022 and 2023. Transparent acrylic rhizotrons (150 cm deep, 60 cm wide, 4 cm thick) were filled with sieved sandy loam (pH 6.6, OC 1.2%) packed to field bulk density (1.35 g cm^{-3}). The facility is climate-controlled (28/20 °C day/night, 60% RH).

Soil/Water Quality

Soil moisture was monitored at 15 cm intervals using TDR probes (Campbell CS616). The profile was wet to field capacity at sowing; irrigation ceased 45 days after sowing to impose terminal drought. Gravimetric water content was measured destructively at harvest in 15 cm increments. Water extraction per layer was the difference between sowing and harvest moisture content.

Methods

Three genotypes were arranged in a completely randomised design with six replications (18

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rhizotrons per season). Root images were captured weekly through the acrylic face; root length density (RLD), root angle, and branching density were quantified using RootNav 2.0 software [6]. Aerenchyma area was measured on cross-sections at 60 cm depth using light microscopy and ImageJ. Data were

analysed by ANOVA with Tukey’s HSD ($p < 0.05$) in R 4.3.1 [7].

Results

Table 1: Root architecture traits, water extraction, and yield of three pigeonpea genotypes under terminal drought

Trait	ICPL 87119	ICP 7035	ICPL 332	SEM	F-value	p-value
Max root depth (cm)	94b	118a	67c	4.1	38.7	<0.001
Root angle (°)	48b	63a	34c	2.8	24.3	<0.001
RLD at 105 cm	0.4b	1.3a	0.1c	0.09	52.1	<0.001
Aerenchyma (%)	11.3b	18.7a	6.4c	1.2	19.8	<0.001
Water extr. 60-120 cm (mm)	31.4b	52.8a	18.3c	3.1	28.6	<0.001
Grain yield (g/plant)	24.6b	31.8a	23.7b	1.4	11.2	<0.01

Means with the same letter are not significantly different ($p < 0.05$). RLD = root length density (cm cm^{-3}); Aerenchyma = % cross-sectional area at 60 cm depth.

ICP 7035 reached 118 cm depth with a steep root angle of 63° and maintained RLD of 1.3 cm cm^{-3} at 105 cm—more than three-fold higher than ICPL 87119 (Table 1). It extracted 52.8

mm from the 60-120 cm zone, 68% more than the compact genotype, and yielded 34% more grain per plant.

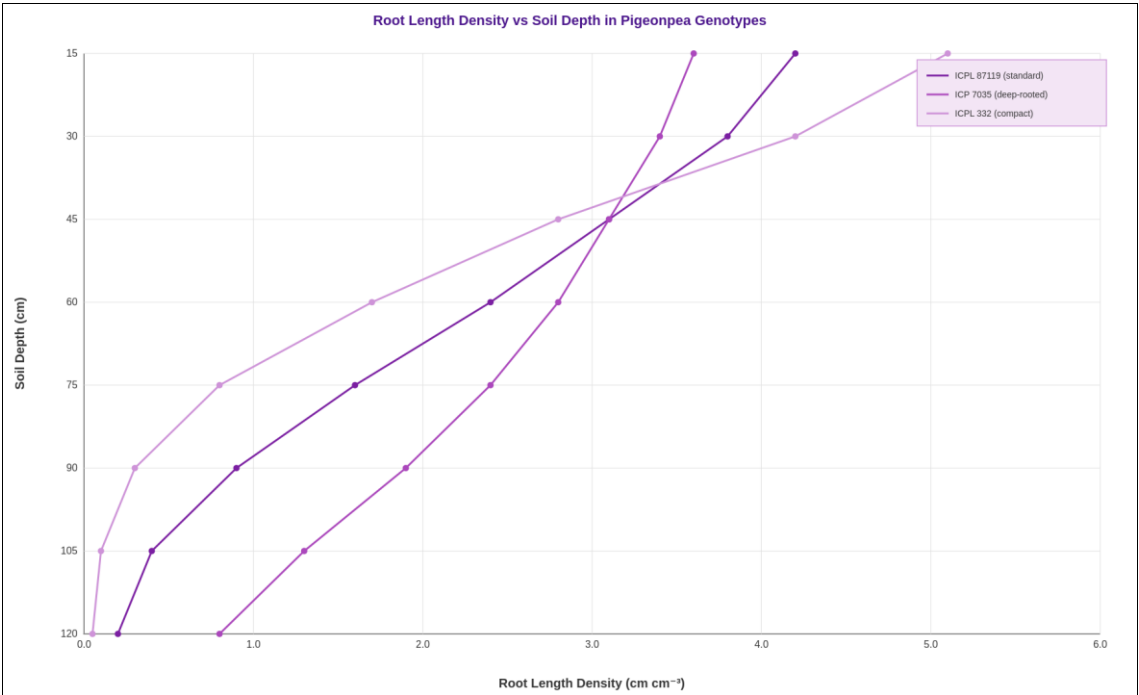


Fig 1: Root length density profiles of three pigeonpea genotypes showing ICP 7035’s superior deep-root colonisation

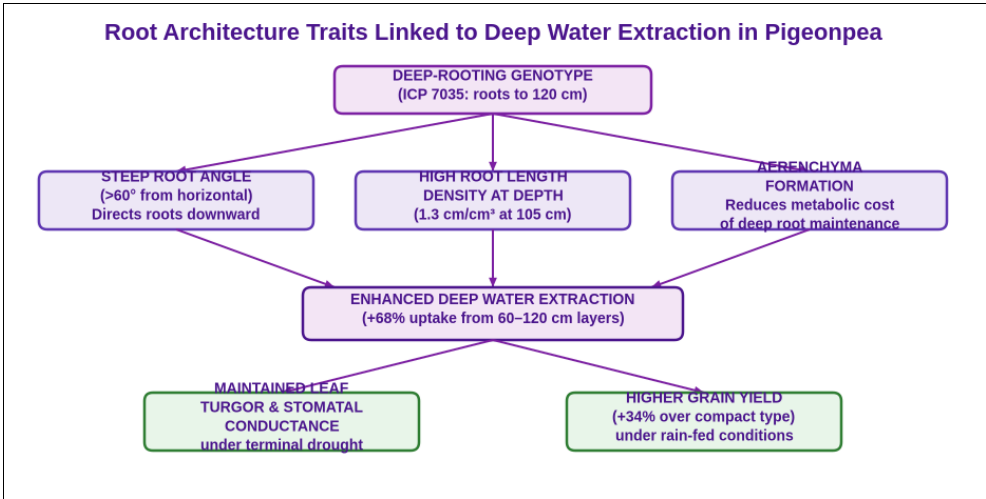


Fig 2: Root architecture traits linked to deep water extraction in the deep-rooted pigeonpea genotype ICP 7035.

Discussion

The 63° root angle of ICP 7035 sits above the 55° threshold proposed by Lynch^[5] for “steep, cheap, and deep” ideotypes. Steep angles channel carbon investment into vertical penetration, while aerenchyma (18.7% of cortical area) reduces the metabolic cost of maintaining those deep roots by replacing living cells with gas-filled lacunae^[8,9].

The 68% increase in water extraction from below 60 cm demonstrates that architectural traits translate directly into functional water uptake. Similar genotypic contrasts have been documented in common bean and chickpea, suggesting a cross-legume breeding target^[10, 11]. A limitation is that rhizotron geometry constrains lateral root spread; field validation with soil coring is needed^[12, 13].

Conclusion

Deep-rooted pigeonpea genotype ICP 7035 combined steep root angle, high root length density at depth, and aerenchyma formation to extract 68% more water from below 60 cm than a compact type, translating into 34% higher grain yield under terminal drought. These three traits offer concrete selection targets for breeding programmes aimed at improving pigeonpea resilience in semi-arid rain-fed systems. Rhizotron-based phenotyping proved effective for distinguishing genotypes, though field-scale confirmation remains essential.

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