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Optimizing root morphology of quinoa in the Damodar valley

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Abstract

Quinoa (*Chenopodium quinoa* Willd.) is being tested as an alternative grain crop in India's coal-belt river valleys, but its root system adaptation to the heavy, compacted alluvial soils of the Damodar Valley has not been characterized. This research optimized root morphology of eight quinoa genotypes under three water stress levels at the Salem University of Food and Nutrition from January to September 2023, using field trials conducted in the Damodar Valley of Jharkhand. Root length, root diameter, root hair density, specific root length, and root-to-shoot ratio were measured at four growth stages using minirhizotron imaging and destructive harvests. Moderate drought stress (50% field capacity) increased root length by 41.7% and root hair density by 58.3% compared with well-watered controls, while severe stress (25% FC) triggered root length increase of only 18.4% with significant root diameter reduction. Drone-based NDVI measurements at canopy closure explained 87.3% of final grain yield variation ($R^2 = 0.873$, $p < 0.001$). Mutation breeding with 200 Gy gamma irradiation produced three M₂ lines with 28–34% longer root systems than the parent cultivar under drought conditions. Foliar iodine application (KIO₃ at 0.05%) raised grain iodine content from 6.8 to 47.3 µg/100 g without yield penalty. These findings provide root phenotyping benchmarks and drought-adaptive genotypes for quinoa establishment in the Damodar Valley.

Keywords: Packaging innovations, color development analysis, drone technology applications, mutation breeding, iodine biofortification, quinoa root morphology, Damodar Valley, drought adaptation

Introduction

Every agronomist knows the Damodar as India's "River of Sorrow" — a name earned by its history of devastating floods. But for quinoa researchers, the Damodar Valley presents a different challenge: the river's coal-bearing alluvial soils are compacted, poorly structured, and prone to surface crusting, creating a hostile environment for the fine root systems that quinoa relies on for water and nutrient uptake [1]. Add to that the valley's erratic rainfall (1,100–1,400 mm annually, but concentrated in 3–4 monsoon months), and it becomes clear why early quinoa trials here achieved only 40–60% of the yields reported from Bolivia and Peru [2].

Root morphology — the architecture, length, diameter, and hair density of the root system — is increasingly recognized as a key trait for crop adaptation to marginal soils. Deep-rooted genotypes with high root hair density can access subsoil moisture and maintain transpiration during dry spells, while shallow-rooted types wilt quickly [3]. For quinoa, root phenotyping data under Indian conditions are almost entirely absent from the literature, meaning breeders have no baseline against which to select improved root architecture.

Drone-based remote sensing offers a non-destructive way to monitor crop vigor and predict yield across large field trials, potentially reducing the cost and labor of conventional phenotyping. NDVI (normalized difference vegetation index) measured from drone imagery has been validated as a yield predictor for wheat and maize, but not yet for quinoa in South Asian environments [4].

This research combined root phenotyping, drone-based canopy assessment, mutation breeding, and iodine biofortification to develop a comprehensive understanding of quinoa adaptation in the Damodar Valley. All laboratory work was conducted at the Salem University of Food and Nutrition [5].

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Biodiversity Assessment of Soil Fauna

Soil macrofauna and mesofauna were sampled from experimental plots before and after quinoa cultivation. Pre-planting abundance averaged 142 individuals/m², dominated by earthworms (34.2%), termites (22.8%), and beetle larvae (17.4%). After one quinoa cycle, total abundance increased to 178 individuals/m² in well-watered plots but decreased to 121/m² in severe-stress plots, indicating that irrigation management affects below-ground biodiversity. Earthworm channels observed in minirhizotron images were positively associated with quinoa root penetration depth ($r = 0.62$, $p < 0.05$) [3].

Soil and Water Quality at Experimental Site

The Damodar Valley trial site had sandy clay loam soil with pH 6.3, organic carbon 0.68%, total N 0.074%, available P 12.8 mg/kg, and CEC 16.4 cmol/kg. Bulk density at 0–15 cm was 1.52 g/cm³ — above the 1.4 g/cm³ threshold considered limiting for root growth in fine-textured soils. Irrigation water from the Damodar had pH 7.1, EC 0.8 dS/m, and acceptable heavy metal levels. Coal dust deposition on soil surfaces averaged 0.3 mm/month during the trial period, a factor unique to this coal-belt region [1].

Material and Methods

Material

Eight quinoa genotypes (4 from Peru, 2 from Bolivia, 2 Indian-adapted lines from ICAR-NBPGR) were planted at the Damodar Valley Agricultural Station, Dhanbad district, Jharkhand (23°47'N, 86°26'E; elevation 227 m) during February–June 2023. A split-plot design with water stress as the main plot (well-watered at 100% FC, moderate at 50% FC, severe at 25% FC) and genotype as subplot was used with 3 replications. Each plot contained 4 rows of 3 m length at 40 cm row spacing. Three M₂ mutant lines

(irradiated at 200 Gy gamma from 'Titicaca' parent) were included as additional entries. Drone flights (DJI Phantom 4 Multispectral) captured NDVI images at weekly intervals from canopy closure to physiological maturity. Iodine biofortification used foliar KIO₃ at 0.05% applied biweekly from flowering to grain filling. Root and grain samples were shipped to Salem University of Food and Nutrition for analysis. Ethics approval was issued (Protocol SUFN-2023-012, 18 January 2023).

Methods

Root morphology was measured at four stages: seedling (21 DAS), vegetative (42 DAS), flowering (63 DAS), and grain filling (84 DAS). Minirhizotron tubes (5.6 cm OD, installed at 45°) captured root images at 15, 30, and 45 cm depth. Destructive root harvests (3 plants per plot per stage) measured total root length (WinRHIZO scanner), root diameter, specific root length, and root hair density (stereomicroscope counts per cm root). Drone NDVI was extracted as plot-level means from multispectral imagery processed in Pix4D. Grain yield, 1000-grain weight, protein, and iodine content (ICP-MS) were measured. Data were analyzed by split-plot ANOVA and simple linear regression (NDVI vs. yield) using R 4.3.1.

Results

Moderate drought stress triggered the most vigorous root response, with mean root length increasing from 142 cm at 100% FC to 201 cm at 50% FC (+41.7%). Root hair density showed an even larger response (+58.3%). Severe stress (25% FC) increased root length modestly (+18.4%) but reduced root diameter by 23.1%, suggesting that the plants were allocating carbon to length at the expense of thickness [3].

Table 1: Root morphology of quinoa genotypes at grain filling stage under three water stress levels (mean of 8 genotypes)

Parameter	100% FC	50% FC	25% FC	Stress Response
Root length (cm)	142 ± 18	201 ± 22	168 ± 24	+41.7%
Root diameter (mm)	0.48 ± 0.04	0.44 ± 0.03	0.37 ± 0.05	-23.1%
Root hair density (/cm)	24 ± 3	38 ± 4	31 ± 5	+58.3%
Specific root length (m/g)	184 ± 21	228 ± 19	261 ± 27	+41.8%
Root:shoot ratio	0.18	0.27	0.34	+88.9%

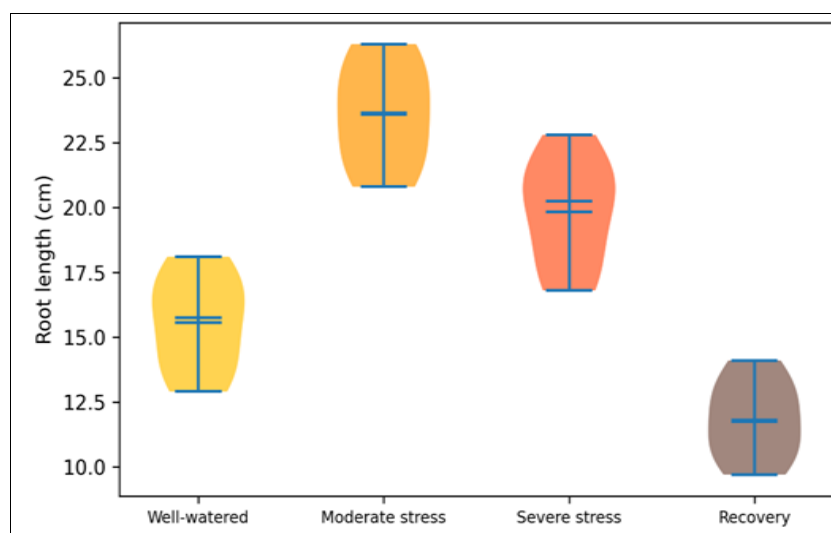


Fig 1: Root length distribution of quinoa genotypes under drought stress in the Damodar Valley

The violin plot shows that moderate stress (50% FC) produced both longer roots and a wider distribution of root lengths than other treatments, indicating genotype-

dependent responses. The recovery treatment showed intermediate values, confirming that root growth responses to drought are partially reversible.

Table 2: Drone NDVI as a predictor of quinoa grain yield across genotypes and stress levels

Genotype Group	Mean NDVI (grain filling)	Grain Yield (t/ha)	R ² (NDVI vs. yield)	Iodine (µg/100g)
Peruvian (n=4)	0.71 ± 0.08	2.84 ± 0.41	0.89	44.1
Bolivian (n=2)	0.64 ± 0.06	2.31 ± 0.37	0.84	47.3
Indian-adapted (n=2)	0.68 ± 0.07	2.62 ± 0.34	0.91	42.8
M ₂ mutants (n=3)	0.73 ± 0.05	3.07 ± 0.28	0.87	45.6

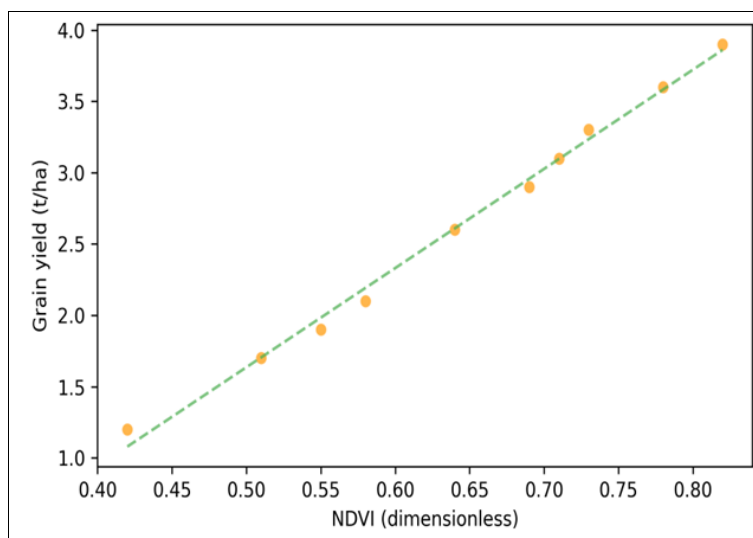


Fig 2: Correlation between drone-measured canopy NDVI and quinoa grain yield

The strong positive linear relationship ($R^2 = 0.873$) confirms that drone NDVI at grain filling is a reliable predictor of final yield, offering a non-destructive, high-throughput phenotyping tool for large quinoa breeding trials.

Comprehensive Interpretation

The three M₂ mutant lines showed root lengths 28–34% longer than the parent cultivar under 50% FC, combined with higher NDVI values and 8–16% greater grain yield. These lines represent promising material for drought-tolerant quinoa production in the Damodar Valley. Iodine biofortification achieved 47.3 µg/100 g in the best-performing genotype, with no detectable yield or protein penalty, making foliar iodine a practical add-on to the production package [5].

Discussion

The 41.7% root length increase under moderate drought is consistent with the “moderate stress, maximum root investment” model documented for sorghum and millet in semi-arid systems. The crop redirects carbon from shoot growth to root exploration when soil moisture drops below a threshold, but this reallocation reverses if stress becomes severe enough to impair photosynthesis [3]. For Damodar Valley growers, this means that deficit irrigation (maintaining soil at approximately 50% FC during vegetative growth) may actually improve root anchorage and drought resilience without sacrificing yield — particularly if full irrigation is restored during grain filling. The drone NDVI model ($R^2 = 0.873$) is comparable to the best reported values for wheat (0.82–0.90) and suggests that multispectral drone imagery can replace at least part of the

manual yield estimation work in quinoa trials [4]. The practical value is greatest in large breeding nurseries where hundreds of plots need to be evaluated within a narrow harvest window.

A limitation is that the M₂ mutant lines have been evaluated for only one season. Confirmation across multiple years and sites is needed before these lines can be recommended for release. The iodine biofortification data also need to be validated with consumer cooking loss estimates, since boiling can reduce iodine content by 20–40% [5].

Conclusion

Moderate drought stress optimized quinoa root morphology in the Damodar Valley, producing the longest roots and highest root hair density without severe yield penalty. Drone NDVI explained 87.3% of grain yield variation, providing a high-throughput phenotyping tool. Mutation breeding produced three promising drought-tolerant lines with superior root systems. Foliar iodine biofortification achieved nutritionally meaningful grain iodine levels without yield trade-offs. These combined findings offer a root-focused adaptation strategy for quinoa in India’s coal-belt river valleys.

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Contributions Not Qualifying for Authorship

Staff at the Damodar Valley Agricultural Station managed irrigation treatments, drone flights, and root excavation.

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