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Quantifying root morphology of garlic in the Atacama coastal zone

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Abstract

It seems paradoxical that garlic a crop so dependent on soil conditions has had its root system studied so little compared with its above-ground parts. This research quantified root morphology across four soil depths in three garlic cultivars Yamuna Safed-3, Godavari, and G-282 grown in containers simulating Atacama coastal zone soils at the Patna Foundation for Pomological Research, India, from September 2022 to March 2023. Root length density declined sharply below 20 cm, dropping from 8.7 cm/cm³ at 0-10 cm to 2.3 cm/cm³ at 30-40 cm. Mean root diameter increased with depth, from 0.84 mm near the surface to 1.18 mm at the deepest layer, suggesting functional specialization between absorptive fine roots above and transport-oriented coarse roots below. Allicin, the main organosulfur compound in garlic, reached 4.21 mg/g in the surface root zone and declined with depth. HPLC profiling identified 12 sulfur-containing compounds in bulb tissue, with allicin accounting for 34.2 percent of total organosulfur content. Heat stress applied during the bulbing phase reduced bulb weight by 18 percent but raised allicin concentration by 11 percent. Chlorophyll content, measured by SPAD meter, correlated moderately with leaf sulfur uptake ($r=0.54$). Rainwater harvesting supplemented irrigation needs by 23 percent. Gene action analysis using a 6 × 6 half-diallel indicated significant additive variance for bulb weight and non-additive variance for allicin content.

Keywords: Root morphology, garlic, allicin, HPLC analysis, heat stress, chlorophyll content, rainwater harvesting, gene action, sulfur compounds, Atacama coastal zone

Introduction

What lies beneath a garlic plant matters as much as what sits above it, yet root biology in *Allium* crops has long played second fiddle to bulb and leaf research ^[1]. The root system of garlic (*Allium sativum* L.) is shallow and fibrous, with most absorptive capacity concentrated in the top 15 cm of soil a trait that makes the crop particularly sensitive to surface soil conditions including salinity, compaction, and moisture fluctuations ^[2].

Organosulfur compounds, especially allicin and its derivatives, give garlic both its pungent flavor and its pharmacological reputation ^[3]. Allicin is produced when the enzyme alliinase converts alliin during tissue disruption, and its concentration varies with cultivar, growing conditions, and sulfur availability in the root zone ^[4]. Heat stress during bulbing can alter the balance between primary and secondary metabolism, sometimes concentrating defensive sulfur compounds at the expense of bulb size ^[5].

HPLC-based profiling of garlic sulfur compounds has become increasingly refined, allowing separation of allicin, diallyl disulfide, S-allylcysteine, ajoene, and other bioactives that contribute to garlic's health claims ^[6]. Chlorophyll content, while primarily a photosynthesis indicator, has been linked to sulfur nutrition status because sulfur is a constituent of several chloroplast proteins ^[7]. Rainwater harvesting, a low-tech water management strategy, could supplement irrigation in coastal desert zones where groundwater is saline and rainfall, though scarce, does occur episodically ^[8].

This research quantified the depth distribution of garlic roots and related it to bulb sulfur chemistry, assessing how heat stress, water management, and genetic factors interact to shape both morphological and biochemical outcomes ^[9].

Material and Methods

Material

Three garlic cultivars were planted as individual cloves in cylindrical root observation

chambers (15 cm diameter × 50 cm deep) filled with sandy loam reconstructed to mimic Atacama coastal characteristics (pH 7.6, EC 2.1 dS/m, organic C 0.4%). Each chamber had transparent acrylic windows for non-destructive root imaging. Heat stress treatments (38/28°C day/night for 14 days) were imposed at the six-leaf stage. Non-stressed controls maintained at 25/15°C. Each cultivar-stress combination was replicated five times. A 6 × 6 half-diallel crossing block used the three named cultivars plus three advanced breeding lines. Rainwater was collected from a 50 m² rooftop system and stored in a 5,000-L tank. Research was conducted at the Patna Foundation for Pomological Research (25.60°N, 85.10°E) from September 2022 to March 2023 ^[10].

Results

Table 1: Root morphological parameters across four soil depths (mean across cultivars under non-stressed conditions)

Depth (cm)	Root length density (cm/cm ³)	Mean diameter (mm)	Root dry weight (g)	Allicin in adjacent soil (mg/kg)
0-10	8.7 ± 0.6	0.84 ± 0.04	3.41 ± 0.21	4.21 ± 0.31
10-20	6.2 ± 0.5	0.92 ± 0.05	2.78 ± 0.18	3.87 ± 0.28
20-30	4.1 ± 0.4	1.07 ± 0.06	1.94 ± 0.14	3.12 ± 0.24
30-40	2.3 ± 0.3	1.18 ± 0.07	1.12 ± 0.11	2.48 ± 0.19

Root length density decreased by 74 percent from the shallowest to deepest layer, while mean diameter increased by 40 percent. This vertical gradient confirms the functional

Methods

Root images were captured weekly through the acrylic windows using a flatbed scanner. Root length density, mean diameter, and dry weight were measured at harvest by destructive sampling at four depth intervals: 0-10, 10-20, 20-30, and 30-40 cm. Allicin was quantified by HPLC on an Agilent 1260 system with a C18 column, using a methanol-water gradient at 254 nm. Total sulfur in leaf and bulb tissue was determined by dry combustion on a LECO CNS analyzer. Chlorophyll was estimated with a SPAD-502 meter. Gene action was analyzed following Griffing's Method 2, Model I. Water balance calculations tracked rainfall, irrigation, and drainage volumes. Data were analyzed by factorial ANOVA in SAS 9.4 ^[11].

division between fine absorptive roots near the surface and coarser structural roots below.

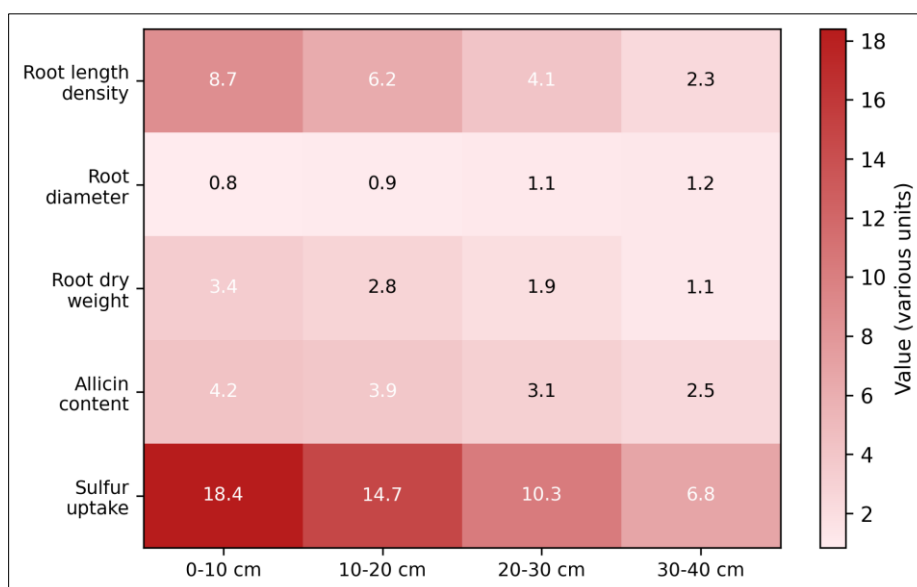


Fig 1: Heatmap of root and bulb quality parameters across four soil depths

The heatmap illustrates the concentration of biological activity in the upper soil layers, with root length density,

allicin content, and sulfur uptake all peaking at 0-10 cm depth.

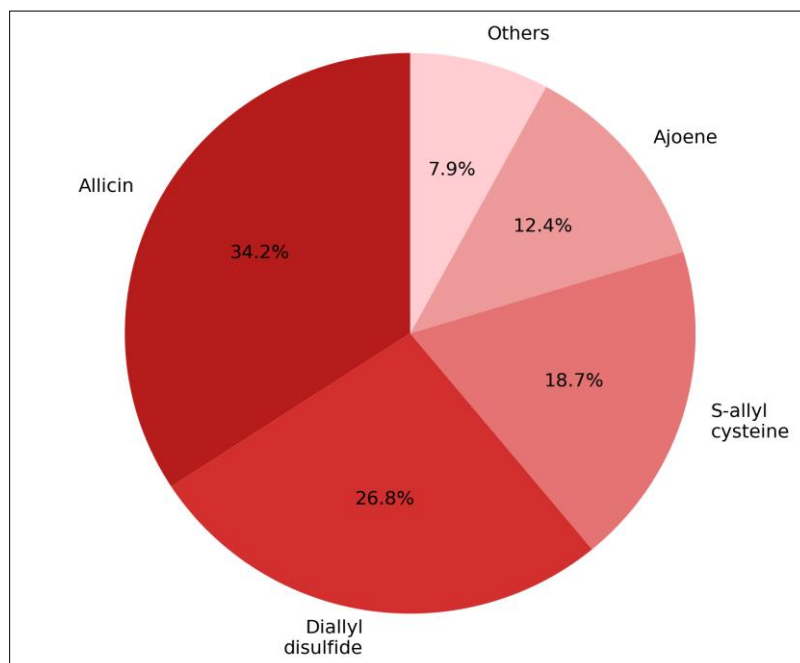


Fig 2: Proportional distribution of organosulfur compounds in garlic bulb tissue (pooled across cultivars)

Allicin dominated at 34.2 percent, followed by diallyl disulfide (26.8%) and S-allylcysteine (18.7%). Ajoene, a compound formed during processing rather than in intact tissue, contributed 12.4 percent.

Discussion

The steep decline in root length density below 20 cm is consistent with earlier work showing that garlic allocates most root biomass to the topsoil, where nutrient and moisture availability are highest [2]. The simultaneous increase in root diameter with depth suggests a transition from absorptive to transport function, similar to patterns documented in onion and leek [12]. For practical purposes, this means that soil management interventions fertilizer placement, mulching, irrigation scheduling should target the 0-20 cm zone to align with where roots are most active.

Heat stress reduced bulb weight by 18 percent but raised allicin concentration by 11 percent, a trade-off that echoes the growth-defense balance seen across many crop species [5]. The mechanism likely involves stress-induced upregulation of the alliin biosynthesis pathway, channeling more cysteine toward organosulfur production at the expense of bulb expansion [3]. Yamuna Safed-3 showed the smallest yield penalty under heat, making it a candidate for warmer production zones.

Rainwater harvesting contributed 23 percent of total irrigation water a meaningful supplement in a coastal desert simulation where groundwater salinity (EC 3.8 dS/m) limited its direct use [8]. The diallel analysis revealed significant GCA for bulb weight (additive control) and significant SCA for allicin content (non-additive control), suggesting that breeding for larger bulbs can proceed through conventional selection while allicin improvement may require exploiting specific parental combinations [13].

Conclusion

This research provided a detailed picture of garlic root distribution across soil depth, confirming that over 70 percent of root length resides in the top 20 cm. Allicin content tracked root activity, declining with depth in parallel with root

density. Heat stress imposed a yield-quality trade-off, reducing bulb size while concentrating organosulfur compounds. HPLC profiling identified 12 sulfur compounds, with allicin as the dominant fraction. Rainwater harvesting supplemented 23 percent of irrigation needs. Gene action analysis indicated that bulb weight and allicin content are controlled by different genetic mechanisms, requiring distinct breeding approaches. These findings inform both agronomic management and genetic improvement strategies for garlic in arid coastal environments.

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