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MORPHOLOGICAL ADAPTATIONS OF *CHENOPODIUM QUINOA*'S ROOTS UNDER STRESS DURING VEGETATIVE DEVELOPMENT

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Abstract

The study evaluated the synergistic interaction between the nutritional and water regimes on the morphophysiological plasticity of two quinoa cultivars, Puno and Vikinga, assessed from the perspective of root system development. The research compares the effectiveness of microbial biostimulation and chemical fertilization under three irrigation regimes (50%, 75%, and 100%). The results indicate that the 75% irrigation regime was the ideal regulatory factor, successfully mitigating chemical stress through dilution and facilitating microbial mobility. In contrast, the 50% regime exacerbated salt toxicity, while the 100% regime limited growth by inducing hypoxia at the root level.
Biochemical profiling proved to be a highly accurate indicator of physiological status; the application of high-dose chemical fertilizers exerted a pronounced toxic effect, with inhibition exceeding 60% regardless of variety. This sharp decline indicates that a critical threshold of osmotic and saline stress was reached, caused by the high concentration of KSC® II.

Key words: *biochemical profile, Chenopodium quinoa, microbial mobility, nutritional regimes.*

INTRODUCTION

The species *Chenopodium quinoa* Willd. is native to the Andean region of South America and has been a staple for pre-Columbian civilizations for over 3 000 years. In recent decades, the recognition of its exceptional nutritional value and remarkable agronomic adaptability has facilitated its transition from a local crop to one of global interest. Against the backdrop of climate change, *Chenopodium quinoa* Willd. is of strategic interest for food security due to its resilience to abiotic stress and its exceptional nutritional profile (Bazile et al., 2016; Jacobsen, 2003; Stoleru et al., 2022a, 2022b). Furthermore, medical research has explored quinoa through computational chemistry, highlighting the potential of its bioactive compounds to inhibit or combat certain viral mechanisms, including those associated with COVID-19. According to recent international resolutions (e.g., UN General Assembly, 2022), quinoa is officially recognized as a functional food with preventive and therapeutic roles in human health management.

The species' adaptation to new areas is conditioned by the plasticity of its root system, whose architecture is decisive for water use efficiency (WUE) and nutrient use efficiency (NUE) under soil stress (González et al., 2015; Nieves-Cordones et al., 2019).

Quinoa is a facultative halophyte characterized by high hardiness, thanks to mechanisms that enable it to withstand various stress factors - such as salinity, drought, and frost. It possesses remarkable genetic diversity resulting from centuries of fragmented cultivation across diverse ecological zones in the Andean region, ranging from Ecuador to southern Chile and from sea level to high-mountain elevations (Vitaneascu et al., 2019; Zhang et al., 2026). This plant's tolerance to abiotic stress (drought, salinity) has led to the development of programs focused on increasing its productive potential.

The quinoa plant's tolerance to abiotic stress (salinity and drought) has led to the development of programs aimed at increasing its productive potential, as it is capable of withstanding soil salinity levels comparable to those of seawater (Manna et al., 2019; Stoleru et al., 2019).

In 1996, the FAO classified quinoa as one of the most promising crops for humanity, not only for its health benefits but also for its versatility, considering it an alternative solution to eradicate global hunger. Subsequently, 2013 was declared the "International Year of Quinoa" by the United Nations, following a proposal endorsed by the FAO (2026).

Root development is influenced by fertilization management in two ways: chemical fertilizers can induce osmotic stress at excessive doses, while biofertilizers stimulate growth and mitigate stress through symbiotic mechanisms (Hinojosa et al., 2018; Ruiz et al., 2017). The effectiveness of these inputs critically depends on the water regime, which modulates nutrient solubility and microbial viability (Chirita et al., 2022; Rădeanu et al., 2025).

The present study analyses root dynamics in the Vikinga and Puno varieties under the influence of the interaction between fertilization and water availability, aiming to optimize sustainable cultivation technologies.

MATERIALS AND METHODS

The research was carried out in a greenhouse of Iasi University of Life Sciences (IULS), Romania, during March to April 2021-2024. vegetation pots (27 cm^3), chemically and organically fertilized substrate, resulted 42 variants, of 3 replicates, 10 plants for each repetition.

The study focused on two varieties of quinoa, specifically Vikinga and Puno, examining their root systems. Both varieties were cultivated under controlled conditions, with temperatures maintained between 16-18ºC during the night and 20-22ºC during the day. Humidity levels were kept at 70-75% for Vikinga and 60-65% for Puno. Additionally, plants were exposed to natural light cycles of 13 hours of light and 11 hours of darkness.

The substrate for experiments consisted of a standardized mixture of Kekkila® peat (600 L), Orgevit® biofertilizer (3.00 kg/m³), and perlite (3.00 kg/m³). This homogenized medium was designed to optimize *Chenopodium quinoa* germination and early root system establishment. Into the substrate was also added Osmocote® Pro, a second-generation controlled-release fertilizer with a high NPK value and a rich content of magnesium and micronutrients (N11:P10:K19:2MgO+ME). It is particularly suitable for use as a base fertilizer mixed into the growing medium due to its steady-release system and a longevity of 5-6 months.

Kekkila® is a specialized peat-based medium for seedling production (0-25 mm), featuring an NPK ratio of 14–16–18 + ME. Its fine-to-medium grain size ensures optimal seed-to-substrate contact, while the pH (5.5-5.9) maximizes micronutrient bioavailability and prevents phosphorus fixation, meeting the specific physiological needs of quinoa.

Perlite® (3.00 kg/m³) was incorporated to optimize the water-to-air ratio. As a chemically inert and non-degradable expanded volcanic mineral, it ensured structural stability throughout the growing cycle.

The fertilizers used were biologic fertilizer, Micoseed MB® and chemical fertilizer, KSC® II, in different quantities.

To test the influence of fertilizer type on plant growth,the following amounts:

- Biological fertilization: 500g/m^3 (F1); 1000 g/m^3 (F2); 1500 g/m^3 (F3) - Micoseed MB®. This biological product is formulated with a consortium of arbuscular mycorrhizal fungi-specifically *Claroideoglomus etunicatum*, *Funneliformis mosseae*, *Glomus aggregatum*, and *Rhizophagus intraradices* - supplemented with beneficial microbes from *Trichoderma*, *Streptomyces*, *Bacillus*, and *Pseudomonas*.
- Chemical fertilization: 1000 g/m^3 (F4); 2000 g/m^3 (F5); 3000 g/m^3 (F6) KSC®. KSC II® is a water-soluble NPK complex (14-40-5 + 13SO_3 and ME) enriched with the Phyt-actyl biostimulator. Its application was prioritized during early vegetation to optimize root system architecture establishment.

The experiment was established using a split-plot, multifactorial design (2×7×3), conducted in pots with a diameter of 17 cm and a height of 12 cm.

Table 1. Experimental design and treatment structure

Cultivar - A	Fertilization - B	Irrigation regime - C
A1 - Vikinga	NF- Control	50%
		75%
		100%
	F1- Micoseed MB® (500 g/m^3)	50%
		75%
		100%

Cultivar - A	Fertilization - B	Irrigation regime - C
	F2 Micoseed MB® (1000 g/m³)	50%
		75%
		100%
	F3- Micoseed MB® (1500 g/m³)	50%
		75%
		100%
	F4- KSC I® (1000 g/m³)	50%
		75%
		100%
	F5 - KSC I® (2000 g/m³)	50%
		75%
		100%
	F6– KSC I® (3000 g/m³)	50%
		75%
		100%
A2 - Puno	NF- Control	50%
		75%
		100%
	F1- Micoseed MB® (500 g/m³)	50%
		75%
		100%
	F2- Micoseed MB® (1000 g/m³)	50%
		75%
		100%
	F3- Micoseed MB® (1500 g/m³)	50%
		75%
		100%
	F4- KSC I® (1000 g/m³)	50%
		75%
		100%
	F5- KSC I® (2000 g/m³)	50%
		75%
		100%
	F6- KSC I® (3000 g/m³)	50%
		75%
		100%

*(NF – control, F1 – 500 g/m³ MB, F2 – 1000 g/m³ MB, F3 – 1500 g/m³ MB, F4 – 1000 g/m³ KSC I, F5 – 2000 g/m³ KSC I, F6 – 3000 g/m³ KSC I).

For the watering of the substrate, water was used at different percentages quantities 50%, 75% and 100% of substrate capacity.

Table 2. Irrigation guidelines for *Chenopodium quinoa* cultivation

Irrigation (%)	Watering interval (days)	Watering rate (mL)
50	2	115-300
75	2	150-450
100	2	225-600

Data on taproot length, obtained through high-resolution 2D scanning and processed using Image Analyser software, were subjected to rigorous statistical analysis to evaluate the impact of the experimental treatments. After removing debris and washing the samples thoroughly, the roots were positioned on a flatbed scanner to capture clear, non-overlapping images, thereby minimizing measurement errors. This digital mapping of root architecture ensured highly accurate quantification of longitudinal growth.

All reported values represent the arithmetic mean, expressed relative to the unfertilized control.

RESULTS AND DISCUSSIONS

An analysis of root system development in the Vikinga and Puno quinoa varieties under different fertilization regimes revealed a complex physiological response. The results showed that the length of the taproot was significantly influenced by both the type of fertilizer and the applied rate.

It is observed that the maximum root length values were recorded in the unfertilized (NF) treatment for both varieties (approximately 200 mm for Vikinga and 202 mm for Puno). This behaviour suggests an adaptation mechanism specific to *Chenopodium quinoa*, whereby, in the absence of sufficient nutrients, the plants allocate their energy resources toward the elongation of the main root in order to explore a larger volume of substrate and find the necessary macro- and microelements.

Biofertilizer applications resulted in a moderate reduction in root length compared to the control (NF), although significant variations were observed between the varieties. The Puno variety demonstrated superior growth performance under biostimulant treatment, maintaining a significantly greater root length in the F2 variant (approximately 157 mm) compared with Vikinga (approximately 105 mm). This difference indicates that the Puno variety responds more effectively to biological fertilization, leading to a stronger root system architecture.

The application of chemical fertilizers (KSC® II) had a marked inhibitory effect on the taproot, with the highest doses (F5, F6) resulting in an inhibition index of over 60% in both varieties. This response indicates a critical threshold for osmotic and salt stress. In contrast, biofertilization was better tolerated, particularly by the Puno variety, which exhibited greater stability (inhibition of only 22.07% in the F2 variant) compared to Vikinga (-47.68%).

Interestingly, in the case of Vikinga, the application of chemical fertilizer at the lowest concentration (F4) was less inhibitory than the average doses of biofertilizer (F2, F3). However, in the case of Puno, biofertilization proved to be better accepted by the plants than any form of chemical fertilization.

When chemical fertilizers were applied at the highest doses (F5, F6), regardless of the variety, inhibition exceeded 60%. This indicates a survival response, with main root growth limited by the high salinity of the substrate.

Correlating the data with irrigation regimes (50%, 75%, 100%) provides an essential perspective for the study, as water acts as a solvent that regulates salt concentration and the mobility of microorganisms in the root zone.

The results indicated that the lowest values were recorded in the treatments under a 50% irrigation regime. This case revealed that water deficiency concentrated salts from the chemical fertilizers (KSC® II), leading to the lowest observed values in F5 and F6, with decreases exceeding 60% (Figure 1). These findings suggest that the roots are not only chemically inhibited, but also experience physiological stress due to water deficit. Under this regime, root length decreases drastically, as the plant cannot compensate for ion toxicity through water absorption (Kang et al., 2022).

The 75% irrigation regime proved to be the most favourable for quinoa, with the highest values. At this moisture level, the osmotic stress induced by chemical fertilizers (F5-F6) was partially mitigated by dilution, allowing the taproot to reach greater lengths than under the 50% regime (Figure 2). Biofertilization, combined with the 75% irrigation level, promoted microbial mobility, resulting in a low inhibition (-22%) for the Puno variety. In contrast, treatments under the 100% WHC exhibited intermediate values (Figure 3).

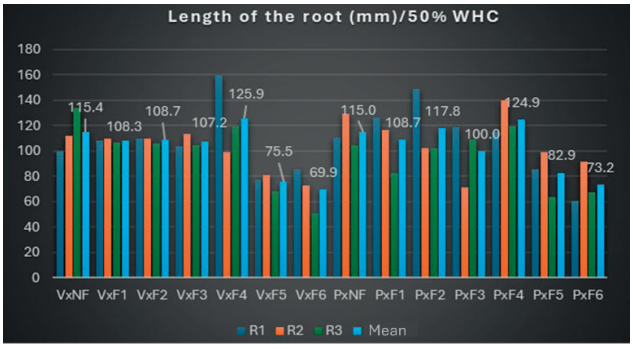

Figure 1. The combined influence of factors on primary root growth (mm)/ 50% WHC
*(NF - control, F1 - 500 g/m³ MB, F2 - 1000 g/m³ MB, F3 - 1500 g/m³ MB, F4 - 1000 g/m³ KSC I, F5 - 2000 g/m³ KSC I, F6 - 3000 g/m³ KSC I)

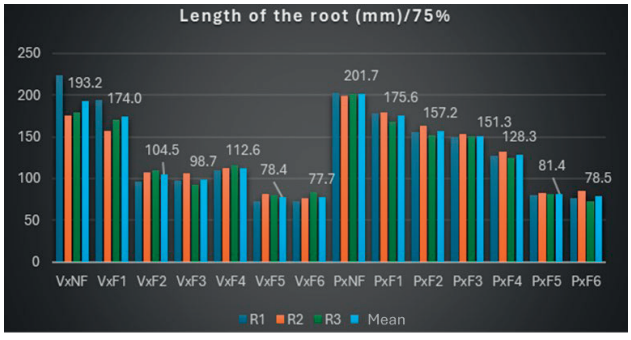

Figure 2. The combined influence of factors on primary root growth (mm)/ 75% WHC
*(NF – control, F1 – 500 g/m³ MB, F2 – 1000 g/m³ MB, F3 – 1500 g/m³ MB, F4 – 1000 g/m³ KSC I, F5 – 2000 g/m³ KSC I, F6 – 3000 g/m³ KSC I)

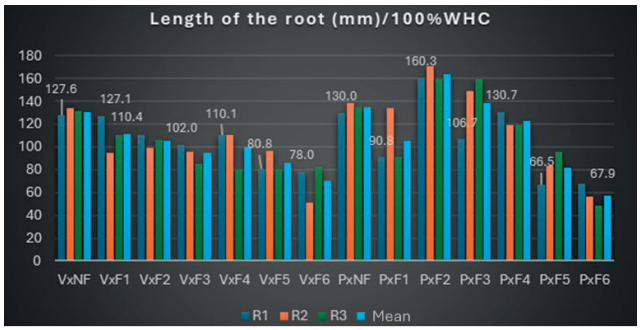

Figure 3. The combined influence of factors on primary root growth (mm)/ 100 % WHC
*(NF – control, F1 – 500 g/m³ MB, F2 – 1000 g/m³ MB, F3 – 1500 g/m³ MB, F4 – 1000 g/m³ KSC I, F5 – 2000 g/m³ KSC I, F6 – 3000 g/m³ KSC I)

Variations in quinoa growth parameters under different irrigation regimes have been documented in previous studies. For instance, Khaled et al. (2021) identified that irrigation treatments applying 80% and 60% of reference evapotranspiration (ET_0) yielded the highest seed production. Furthermore, Mirsafi et al. (2024) noted an increase in the root-to-shoot ratio as the volume of applied irrigation water decreased. According to Mirsafi et al. (2024), the variation in root length is influenced by the irrigation regime since roots are the primary organs for absorbing water and nutrients. Consequently, their distribution in the soil is closely linked to the soil's water content and nutrient uptake capacity. Water scarcity often drives plants to develop deeper root systems by promoting elongation. Conversely, excessive water can lead to oxygen deprivation, which inhibits root growth and may cause decay. Mild drought conditions can enhance the root-to-shoot ratio as plants search for moisture, while prolonged water saturation restricts essential oxygen availability and may result in root rot (Ramachandran et al., 2020).

CONCLUSIONS

The absence of fertilization resulted in the greatest root elongation in both varieties. This behaviour confirms the high plasticity of *Chenopodium quinoa* and its ability to redirect energy resources toward substrate exploration when nutrient availability is limited.

The Puno variety demonstrated superior stability and adaptability compared to Vikinga, maintaining a more robust root architecture under biofertilization. Specifically, in the F2 variant, Puno exhibited an inhibition of only 22%, whereas Vikinga showed a drastic decrease of nearly 50%.

High doses of chemical fertilizers (F5, F6) exerted a pronounced toxic effect, with inhibition exceeding 60% across both cultivars. This significant decline indicates that a critical threshold for osmotic and saline stress, triggered by the concentration of KSC® II, was reached.

Optimal Regime (75%): proved to be the ideal regulatory factor, effectively mitigating chemical stress through dilution and enhancing microbial mobility within the root zone.

Limiting Regimes: In contrast, the 50% regime exacerbated salt toxicity due to concentration effects, while the 100% regime restricted growth by limiting oxygen availability at the root level (hypoxia).

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