REVIEW ARTICLE
AGROBIOLOGICAL RECORDS
ISSN: 2708-7182 (Print); ISSN: 2708-7190 (Online)
Open Access Journal

THRIVING IN ADVERSITY: QUINOA'S RESPONSE TO DROUGHT AND THE PROMISE OF OPTIMIZED WATERING

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ABSTRACT

Quinoa (*Chenopodium quinoa Willd.*) has emerged as a vital crop addressing the global challenge of food security amid climate change, population growth, and increasing hunger. In 2025, over 295 million people faced acute hunger, aggravated by climate extremes disrupting traditional food systems. Quinoa's resilience to adverse conditions such as drought, high salinity, frost, and poor soils, combined with its superior nutritional profile complete protein, fiber, and essential minerals makes it a promising climate-resilient superfood. Originating in the Andean region about 5,000–7,000 years ago, quinoa's domestication and cultivation are deeply rooted in indigenous practices, preserving over 3,000 local varieties adapted to diverse microclimates. Despite historical suppression, quinoa has experienced a global resurgence, now cultivated in at least 95 countries ranging from sea level to 4,000 meters in altitude, delivering yields from <1,000kg/ha in marginal conditions to >9,000kg/ha under intensive management. Recent studies document quinoa's drought tolerance mechanisms: antioxidant enzyme activities increase under stress, osmoprotectants accumulate, and genotypic variation permits maintenance of yield despite water limitations. For example, deficit irrigation strategies applying 40–75% of crop evapotranspiration sustain yields of approximately 1,400–1,800kg/ha while improving water use efficiency by up to 67%. Seed priming with selenium (6 mg/L) and use of organic amendments like biochar markedly enhance drought resilience and yield. Furthermore, quinoa's molecular drought responses involve upregulation of aquaporin channels, LEA proteins, and transcription factors (AP2/ERF, NAC), modulated via abscisic acid signaling. Breeding efforts integrating phenotypic, physiological, and genomic data are accelerating development of drought-tolerant genotypes, while precision irrigation technologies such as AI-based phenotyping and IoT-controlled irrigation hold promise for optimizing water use. However, challenges remain, including a lack of standardized irrigation protocols across diverse ecotypes, economic constraints in low-input systems, and increasing drought frequency due to climate change. Bridging these gaps through genotype-specific water management and adoption of sustainable agronomic practices is essential for quinoa's continued contribution to resilient global food systems.

Keywords: Quinoa, Drought tolerance, Water use efficiency, Deficit irrigation, Molecular breeding, Nutrient management.

Article History (ABR-25-038) || Received: 24 Apr 2025 || Revised: 25 Jun 2025 || Accepted: 19 Jul 2025 || Published Online: 15 Aug 2025

1. INTRODUCTION

In 2025, over 295 million people faced acute hunger, a trend primarily driven by conflict, climate extremes, and economic instability. Hunger and malnutrition are increasing worldwide, with climate change worsening harvest failures and supply chain disruptions. Traditional crops are under threat, and searching for resilient, nutritious alternatives is more urgent than ever. Elevated food price inflation impedes global hunger and malnutrition reduction, disproportionately affecting vulnerable groups. The State of Food Security and Nutrition in the World 2025 report urges coherent fiscal and monetary policies, open trade, social protection, improved data, and resilient agrifood systems to reignite progress toward SDG targets by 2030 (Unicef, 2024).

Food security, once a developing world concern, is now global. It's a multidimensional concept resting on four pillars: availability, access, utilization, and stability. There are arguments to add food agency, sovereignty, and sustainability, forming a six-pillar framework. Measuring food security is challenging due to diverse analytical levels (macro, meso, micro) and numerous metrics. African development projects must define food security precisely to assess success beyond mere food production increases (Makombe, 2023). An article examines

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Open Access Journal

development banks' evolving role, particularly post-crisis. It details their conceptual approaches, funding, business models, and mandates. The paper highlights their economic contributions and proposes an "added value matrix" to showcase their strategic importance (Bentouir, 2022). Socio-Cultural Analysis (SCA) must evolve for future conflicts and declining budgets, moving beyond Afghanistan and Iraq. A volume, influenced by "Left of Bang," addresses challenges in collecting socio-cultural information for "phase zero" operations. Its short, accessible articles are for planners, operators, and policymakers, aiming to improve DOD's SCA capabilities (Brown).

Quinoa (*Chenopodium quinoa* Willd.), revered by the Incas, is a "superfood" due to its complete protein, healthy fats, and rich nutrient profile. It offers numerous health benefits, reducing risks for various diseases. Its adaptability to diverse climates makes it ideal for cultivation in developing regions, offering a powerful solution to global hunger and malnutrition (Singh & Singh, 2016). Quinoa greens, like the grain, are a nutrient-dense "superfood" with diverse health benefits (antimicrobial, anticancer, etc.). They offer protein, essential minerals, and omega-3s, are gluten-free, and can be grown year-round in various conditions with minimal resources. Despite this, their consumption is uncommon. It highlights their nutritional and functional potential to combat malnutrition and enhance food security (Pathan & Siddiqui, 2022). A book explores quinoa and chia, highlighting their nutritional value as gluten-free superfoods rich in bioactive compounds, vitamins, and minerals. It emphasizes their adaptability to climate change and details processing methods, functional properties, and analytical profiles. The book aims to boost production, enhance food and health security, increase farm output, and promote food industries (Nehra & Gahlawat, 2022).

Facing rising populations and climate change, quinoa offers a sustainable, highly nutritious solution. This "complete protein" pseudo-cereal, rich in essential amino acids, fiber, and vital minerals (iron, magnesium, phosphorus, potassium), supports overall health, preventing ailments like anemia and promoting muscle, nerve, and bone health. Its therapeutic properties include antioxidant, antidiabetic, and anti-inflammatory effects. Crucially, quinoa thrives in diverse, adverse conditions, unlike conventional crops, making it a robust option for bolstering global food security (Gaur et al., 2025). Quinoa, a South American pseudo-cereal from the Chenopodiaceae family, is globally consumed for its high protein and rich nutrient profile, including vitamins (C, E, B complex) and essential minerals. Its phytochemicals offer significant health benefits, used in treating various health problems. This study will examine quinoa's properties and its application in bread-making, analyzing the bread's texture, sensory attributes, and chemical composition (Mohyuddin, 2019).

Quinoa contains 12–22% protein, higher than rice, barley and corn. It's one of the rare plant foods that provide all nine essential amino acids—making it a 'complete' protein, comparable to animal products like beef. Particularly, it is rich in lysine and histidine, essential for growth and health. Its proteins are also highly digestible, even after cooking (Xi et al., 2024). One cup of cooked quinoa delivers about 5g of fiber. Its fiber content is superior to most grains and supports digestive health, helps regulate blood sugar, and reduces the risk of chronic diseases (Sharma et al., 2025). Quinoa is an excellent source of magnesium, manganese, copper, iron, phosphorus, and zinc. It also contains important vitamins such as folate, vitamin B6, riboflavin, and vitamin E. 100g of quinoa can satisfy much of an adult's daily needs for magnesium, copper, and iron (Hernández-Ledesma, 2019). The minerals in quinoa are present in forms efficiently absorbed by the body. Sprouting (germination) further increases the availability of iron, calcium, and zinc by breaking down compounds that would otherwise limit absorption (Bordoni et al., 2025).

2. OVERVIEW OF QUINOA

2.1. Quinoa's Origin and Traditional Cultivation in the Andean Region

Quinoa (*Chenopodium quinoa Willd.*) originated and was domesticated in the Andean region of South America. Archaeobotanical and genetic evidence indicate domestication may have begun as early as 5,000–7,000 years ago near Lake Titicaca, a region straddling modern-day Peru and Bolivia. Early Andean societies recognized quinoa's adaptability and high nutritional value, establishing it as a food staple (Bazile et al., 2016). It had spiritual and cultural significance for pre-Columbian Andean civilizations, including the Incas, who referred to it as the "mother grain" and incorporated it into rituals, ceremonies, and daily diets. It served as a key component in agricultural and spiritual life, valued for its resilience on high-altitude, marginal lands (Camaggio & Amicarelli, 2014).

In regions like the Peruvian Altiplano (notably around Lake Titicaca), indigenous Aymara and Quechua communities have maintained quinoa's genetic diversity through traditional systems known as *aynokas*. These are ancestral, landscape-scale crop rotation and communal land management systems that enable adaptation to the Andes' microclimates. Communities practicing *aynokas* cultivate and preserve over 3,000 local quinoa varieties, strengthening both biodiversity and climate resilience (Seligmann, 2023). Andean farmers employed diverse techniques—crop rotation, composting, integration with animal husbandry, and stone-bordering hillside plots—to minimize frost damage and maximize water efficiency. These community-based practices, rooted in deep local ecological knowledge, sustained quinoa cultivation through droughts, poor soils, and climatic variability (Angeli et al., 2020).

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A study evaluated 268 Ecuadorian Andean quinoa landraces from two collection periods (1978-1988 and 2014-2015) to assess phenotypic diversity and conservation status. High variability was found, with significant differences between collections. Notably, saponin presence drastically reduced from 100% to 18% in recent accessions. Some newer Chimborazo accessions show promise for breeding, exhibiting high yields and low saponin, aiding future management and conservation efforts for this vital ancestral crop (Delgado et al., 2024). Following the Spanish conquest, quinoa was suppressed as "Indian food" and lost lands to European crops, but it never vanished entirely. In remote Andean communities, it persisted as a traditional staple and, starting in the late 20th century, experienced a resurgence due to international recognition and scientific validation of its nutritional benefits (Toro-Mayorga, 2023).

2.2. The Paradox: Quinoa's Reputation for Drought Tolerance vs. its Potential Yield Response to Optimal Water Supply

Quinoa's drought tolerance and its yield response to water availability have been extensively studied in recent years, revealing a multifaceted adaptation to water stress alongside capacity for enhanced yield under optimal water conditions (Table 1; Table 2; Fig. 1). A recent study evaluated 20 quinoa genotypes under water deficit in hydroponic and pot experiments to identify drought-tolerant varieties for food security. Researchers measured growth, yield, and physiological traits (e.g., chlorophyll, proline, MSI). Results showed genotypes 16, 10, 1, 4, 5, 7, and 12 as drought-tolerant with high yields and improved physiological characteristics, while others performed poorly. All studied traits strongly correlated with the drought tolerance index, making them useful screening criteria for breeding programs (Saddiq et al., 2021). Another study assessed four quinoa genotypes under varying irrigation during grain filling. Yield significantly decreased with diminishing water, while leaf water potential (LWP) and maximum quantum yield (Fv/Fm) also varied. 'Cahuil' consistently yielded highest. Protein content remained stable across irrigation levels. Quinoa can be grown with irrigation deficit during this stage, maintaining both yield and nutritional quality (Valdivia-Cea et al., 2021).

Table 1: Quinoa's Drought Tolerance Traits and Yield Response to Water Availability (Recent Studies 2020–2025)

Key Findings on Drought Tolerance	Yield Response to Optimal Water	Notes on Genotypic Variation	References
Quinoa accumulates chlorophyll and sugars under drought; antioxidant enzymes activated; maintains physiological function under PEG-induced drought	Yield reduction under severe drought; moderate drought tolerance mechanisms identified	Genotypic variation in drought response was noted	(Bao et al., 2025)
Quinoa performed well in drought vs. irrigated and rainfed conditions in U.S. Midwest trials	Some genotypes showed higher yields under drought than irrigated; no significant yield difference between irrigated and rainfed	Positive correlation plant height & yield; genotypic consistency across environments	(Pathan et al., 2023)
Differences in antioxidant enzyme activity, stomatal density among cultivars contribute to drought tolerance	Cultivars with higher antioxidant activity and lower stomatal density maintain better growth and yield under drought	'Chaidamuhong' cultivar more drought tolerant than others	(Zhang et al., 2022)
Multi-omics study: drought-tolerant cultivar (LL1) shows enhanced abscisic acid and osmotic stress responses	Yield potential linked to metabolomic and gene expression indicating stress adaptation	Transcriptomic profiles differentiate drought-tolerant and sensitive cultivars	(Wang et al., 2024)
Quinoa inherently drought tolerant; varieties differ in tolerance	Optimal irrigation improves yield but drought-tolerant varieties maintain reasonable yields with less water	Genetic and environmental factors modulate yield potential	(Delgado et al., 2025)

The drought responses of two djulis (red and yellow) and one quinoa variety. Severe drought (8% VWC) reduced growth and increased oxidative stress in all, with yellow djulis most affected. Quinoa and djulis showed increased antioxidant enzyme activity, maintaining stable AsA/DHA ratios. Quinoa increased sugars and proline, while djulis (especially yellow) significantly boosted proline and sugars, indicating distinct drought tolerance mechanisms (Lin & Chao, 2021). Moreover, it is also investigated quinoa's drought tolerance using tolerant (D2) and sensitive (ZK1) varieties. Under drought, D2 showed increased chlorophyll and better photosynthetic performance than ZK1. Metabolomic analysis revealed upregulation of specific metabolites (e.g., 12(R)-HETE, stachyose) and enrichment in unsaturated fatty acid biosynthesis and glycerophospholipid metabolism. Findings suggest quinoa combats drought by accumulating chlorophyll/sugars and activating lipid metabolism, offering insights for drought-tolerant quinoa breeding (Bao et al., 2025).

Another study investigated drought-tolerant (LL1) and sensitive (ZK1) quinoa cultivars using physiological, transcriptomic, and metabolomic analyses. LL1 showed unique enrichment in abscisic acid and osmotic stress responses. Both cultivars activated glycerophospholipid and cysteine/methionine metabolism. "α-linolenic acid

ISSN: 2708-7182 (Print); ISSN: 2708-7190 (Online)
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metabolism" was key in both, especially LL1, suggesting methyl jasmonate's role in drought response, providing insights for quinoa drought resistance breeding (Wang et al., 2024). The impact of 2% woodchip biochar on three quinoa varieties (Titicaca, Quipu, UAFQ7) under drought. Drought significantly affected growth differently among varieties; UAFQ7 showed superior vegetative growth, while Quipu excelled in yield-contributing traits. Biochar application consistently enhanced root development and overall plant growth, significantly increasing root biomass. However, a potential trade-off between vegetative growth and panicle development was observed in UAFQ7 with biochar. Further research on physiological responses like stomatal regulation and yield mechanisms is recommended (Akram et al., 2024).

2.3. Adaptability to Marginal Soils, Salinity and Varying Altitudes

Quinoa thrives in poor, sandy, and low-fertility soils where many staple crops underperform. Recent field experiments demonstrated its growth and respectable seed yields on saline soils up to 15 dS/m, with mulching and organic amendments (like biochar) further improving quinoa growth, yield, and water productivity even in saline semi-arid environments. Genotypic variation also allows selection of quinoa lines with superior salt and drought tolerance (Yousfi et al., 2025). Organic mulch significantly improved quinoa's water productivity (2.20 kg/m³) with saline irrigation compared to a non-mulch treatment (1.53 kg/m³). This shows that mulching is effective for growing quinoa in saline, semi-arid environments (Soomro et al., 2025). In a study of five quinoa genotypes, native fungal endophytes were found to significantly enhance salt tolerance and seed quality. E+ plants showed improved photochemical efficiency, higher CqNHX1 gene expression, and up to 30% greater survival under high salinity, with no negative effects under normal conditions (Miño et al., 2025).

Traditionally cultivated from sea level up to 4,000m in the Andes, quinoa's genetic diversity includes ecotypes specifically adapted to high mountain “Altiplano” climates, temperate valleys, and coastal plains, supporting agricultural resilience across a spectrum of temperature and altitude extremes. Its tolerance to both frost and high heat has enabled successful cultivation in cold, saline highlands and in warmer drylands (Bazile et al., 2016). A global review of quinoa cultivation revealed that the crop can thrive in new regions, with some yields surpassing those from its native Andes. The study found that while quinoa has low input needs, it responds positively to increased fertilizer and water. It also identified key challenges, including weed control, pests, and post-harvest saponin removal (Taaime et al., 2023). Five quinoa genotypes were evaluated in Oman over three years. Results showed that genotypes, locations, and years significantly impacted yield. Amarilla Sacaca was the highest-yielding genotype, particularly at the Rumais location (8.86 t ha^{-1}). The study confirms quinoa's adaptability to Oman's agro-ecological conditions, with an average yield of 3.83 t ha^{-1} (AlKhamisi et al., 2021).

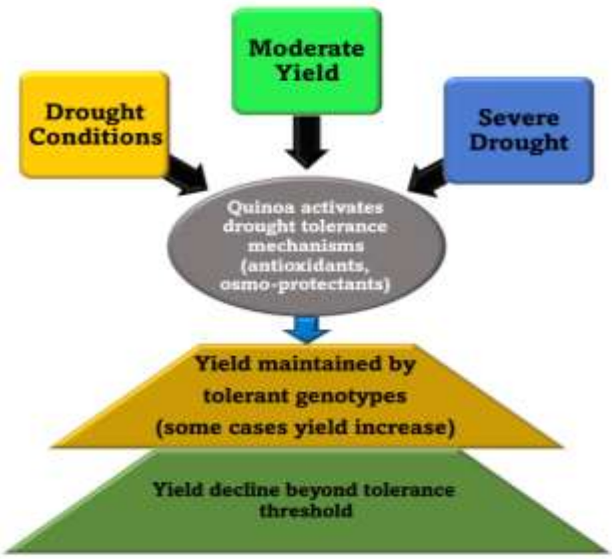

Fig. 1: Conceptual Model of Quinoa's Drought Adaptation vs. Yield Response.

Bridging the gap between quinoa’s natural resilience and the need for strategic water management in diverse environments is essential to optimize its contribution to sustainable food systems, especially under the increasing pressures of climate change and limited water resources (Table 3). Quinoa is inherently drought-tolerant, exhibiting physiological and biochemical strategies like rapid stomatal closure, sunken stomata, restricted root growth, and accelerated leaf senescence. These traits allow it to maintain growth and seed yield even with limited water supply (Pradhan et al., 2025). Significant differences exist between quinoa cultivars regarding resilience, yield, and adaptation to specific water regimes, reinforcing the importance of selecting the right genotype for each environment (Aliaga Lordemann et al., 2024; Nguyen et al., 2024).

Early sowing dates align critical growth stages with optimal temperatures, reducing vulnerability to drought and maximizing seed yield. Fertilizer management matters: moderate nitrogen application (e.g., 100kg/ha) in poor soils optimizes plant performance without excessive input or emissions (Maliro & Njala, 2019). Conservation agriculture techniques, such as biochar amendment and no-till, enhance soil organic matter, moisture retention, and root development—vital for water-limited conditions (Dao et al., 2020).

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Table 2: Recent Findings on Quinoa Drought Tolerance and Yield Response

Trait/Aspect	Findings	References
Antioxidant enzyme activity	Increased SOD, APX, GR under drought, protecting cells from oxidative damage	(Wang et al., 2024)
Osmoprotectant	Proline and soluble sugars accumulate, aiding osmotic balance	(Huan et al., 2022)
Photosynthesis & chlorophyll	Maintenance or increase with drought in tolerant cultivars	(Huang et al., 2022; Wang et al., 2024)
Root system	More extensive root growth improves water uptake under drought	(Akram et al., 2024)
Hormonal regulation	ABA mediates stomatal closure to conserve water	(Aslam et al., 2020)
Metabolomic pathways	Unsaturated fatty acid and α-linolenic acid metabolism enhanced during drought	(Nadali et al., 2021)
Genotypic diversity	Ecotypes and cultivars differ in drought tolerance strategies and yield stability	(Hussain et al., 2020; Thiam et al., 2021)
Yield response to optimal water	Yield increases with irrigation, but some drought-tolerant genotypes yield well under drought	(da Silva et al., 2021; Salim et al., 2020)
Drought escape varieties	Short-duration types avoid drought by rapid life cycle completion	(Asati et al., 2022; Nadeem et al., 2024)

Studies from Bolivia reveal a high water footprint (1,728L/kg) when productivity and soil fertility are low, indicating that improving yield through better soil management and irrigation technology sharply increases water-use efficiency (Aliaga Lordemann et al., 2024). Practices like planting at the start of rainy seasons, adjusting plant density, and guiding water to roots with furrows further optimize water use in rainfed systems. Genotype-Environment interaction studies highlight that the performance of specific quinoa varieties varies widely with water regime and environment (Aliaga et al., 2025). Strategic water management must be customized: Some regions and genotypes show better yield under deficit irrigation, while others may require more water depending on soil and climate conditions.

Table 3: Bridging the Gap

Strategy/Factor	Key Insights	Recent References
Deficit irrigation	Maintains yield, increases water-use efficiency	(Harisha et al., 2025; Nanduri et al., 2019)
Conservation agriculture	Enhances soil moisture and yield in water-limited systems	(Awa et al., 2024)
Genotype selection	Matches crop to local drought/water regime conditions	(Condori-Ataupillco et al., 2025)
Fertilizer and sowing timing	Optimizes yield, reduces emissions and water demand	(Pradhan et al., 2025; Sun et al., 2025)
Practical adaptation	Rainy season planting and furrow irrigation improve outcome	(Mendoza-Márquez et al., 2025)

2.4. Molecular Responses to Drought in Quinoa

Aquaporins are membrane-channel proteins that regulate water transport across cellular membranes. During drought, certain aquaporin genes (particularly plasma membrane intrinsic proteins, PIPs) are upregulated—primarily in roots—to enhance water uptake and help maintain plant water status under stress (Table 4). Studies confirm that changes in aquaporin expression during drought in quinoa mainly occur in roots, adapting the plant's hydraulic conductance to water scarcity (Nakagawa, 2022). Exogenous application of silicon and molybdenum improved drought tolerance in quinoa. The combined treatment enhanced growth, physiological, biochemical, metabolic, and hormonal attributes, while reducing electrolyte leakage and stress-related compounds. This was linked to the upregulation of the *CqSNRK2.10* gene, suggesting that Si and Mo in combination is an effective strategy to mitigate drought stress (Askar et al., 2024).

LEA proteins are encoded by stress-responsive genes highly induced under dehydration. They stabilize cellular components and protect proteins and membranes from desiccation. Upregulated LEA protein gene expression in quinoa and related plants is a hallmark of improved drought tolerance, supporting cell survival under water deficit (Abdoli Nasab & Mortezavi, 2021). Researchers identified 83 LEA proteins in *M. sativa*, classifying them into seven groups. They found that MsLEA69 enhances tolerance to drought, salinity, and cold stress, suggesting its potential for improving stress resistance in alfalfa (Wang et al., 2025). Study identified eleven dehydrin (DHN) genes in quinoa, classifying them into four structural subgroups. The analysis revealed that CqDHN4s are upregulated in response to salt stress across all varieties, while CqDHN1s are downregulated in a more salt-tolerant variety. This suggests that these DHN subgroups have distinct roles in the plant's adaptation to salinity (Melgar et al., 2024).

Transcription factors (TFs) orchestrate the activation of stress-responsive genes. APETALA2/ethylene-responsive element binding factors regulate morphogenesis, activate osmoprotectant genes, and integrate hormonal and environmental signals. Their upregulation under drought triggers cascades involved in protective metabolism

ISSN: 2708-7182 (Print); ISSN: 2708-7190 (Online)
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and developmental adjustment. Specific ERF genes (such as CqDREB05, CqERF15) are strongly induced in quinoa in response to drought and show conserved function with orthologs in Arabidopsis and other crops (Bakhtari et al., 2024; Zhu et al., 2024). NAC, MYB, HD-ZIP, bHLH, these TFs regulate antioxidant enzymes, membrane protection, and secondary metabolite production. They create complex networks that fine-tune gene expression for maximum stress resilience (Sahid et al., 2023; Sun et al., 2022). Many of these TFs act downstream of ABA, a key drought hormone. ABA-responsive TFs—such as ABF/AREB (binding to ABRE elements)—activate drought response genes, including LEAs and aquaporins, promoting stomatal closure and metabolic adaptation (Hou & LIU, 2025).

Table 4: Selected Molecular Components in Quinoa Drought Response

Component	Role in Drought Response	References
Aquaporin genes (PIP subfamilies)	Enhance root water uptake, regulate hydraulic conductance	(Esmaielzehi et al., 2024) (Alharby et al., 2022)
LEA protein genes	Protect proteins/membranes from dehydration damage	(Jia et al., 2022) (Xiao et al., 2007)
AP2/ERF transcription factors	Regulate stress, activate protective genes (osmolytes, antioxidants)	(Bakhtari et al., 2024)
NAC, MYB, HD-ZIP, bHLH TFs	Activate networks for antioxidant defense, signaling	(Hu et al., 2022; Lu et al., 2025)
ABA-responsive TFs (ABF/AREB)	Trigger ABA signal to activate drought-protective genes	(Park et al., 2025)
Differentially expressed stress genes	Metabolic adaptation (starch metabolism, flavonoids, etc.)	(Bhargava & Sawant, 2013; Wang et al., 2024)

2.5. Nutrient Management: Role of Fertilization in Enhancing Drought Resilience and Water Use Efficiency

Strategic application of nitrogen fertilizer improves quinoa's growth, seed yield, and water productivity, especially in drought-prone marginal environments. Higher nitrogen rates (up to 100kg/ha) can enhance photosynthetic rate, biomass and protein content under water stress, but excessive rates may increase environmental footprint. Seed priming with selenium (6mg/L) significantly improves drought tolerance, health, and yield by boosting chlorophyll content, stomatal conductance, osmotic potential, and water use efficiency, while protecting cellular structures and photosynthetic machinery (Hinojosa et al., 2018). Drought severely reduces quinoa yield, with the seed-filling stage being the most vulnerable. However, priming quinoa seeds with selenium, particularly at 6 mg L^{-1}, was found to effectively mitigate these negative effects (Table 5). This treatment significantly improved yield, physiological, and biochemical traits, and enhanced grain quality by increasing protein, phosphorus, and potassium content (Raza et al., 2024).

Another study investigated how different fertilizer types and nitrogen rates affect quinoa cultivation in high-altitude environments. The results demonstrated that applying slow-release fertilizer (SRF) with 120 kg ha^{-1} of nitrogen was most effective. This combination improved soil water retention, water use efficiency, and soil nutrient availability, leading to a significant increase in quinoa biomass and yield, offering a viable drought-resistant strategy (Sun et al., 2025). Applying 3t ha^{-1} of biochar to soil significantly enhanced quinoa growth and yield under water stress. The biochar improved soil hydraulic properties, increasing water retention and absorption. This treatment increased quinoa yield from 3.18 to 4.22t ha^{-1} and boosted key biometric characteristics, effectively mitigating the negative impacts of prolonged irrigation intervals (Condori-Ataupillco et al., 2025).

Drought-stressed quinoa is often more susceptible to some pathogens, especially fungal diseases such as *downy mildew* (*Peronospora variabilis*), which can cause up to 58–100% yield losses in susceptible cultivars (Afzal et al., 2023). Root rot, caused primarily by *Fusarium solani* f. sp. *pisi*, is a significant problem for peas in New York. A study from 2007–2011 evaluated pea varieties for tolerance. While all were susceptible, some varieties like Grundy and Pendleton showed intermediate tolerance, with root rot severity ratings below 6.0, while others like June and Romance were highly susceptible (ABAWI et al., 2015).

Drought-stressed, nutrient-deficient plants have fewer resources to allocate toward chemical and physical defenses, making them more vulnerable to insect pests like borers, moths (*Eurysacca melanocampta*) and cutworms (Schrader et al., 2025). Multi-trait breeding is a crucial agricultural strategy for developing crops that are more resilient to pests and abiotic stresses while simultaneously improving yield. This approach combines traditional breeding with modern genetic, genomic, and biotechnological tools like genomic selection and CRISPR-Cas9. The goal is to address global food security challenges by creating crops with enhanced resistance and productivity (Pandiyan et al., 2025). A study surveyed 210 plant physiology professionals to understand how they use molecular techniques in stomatal research. Findings revealed no significant correlation between a researcher's experience or education and their use of techniques like CRISPR-Cas9 or RNAi. The study recommends functional training for these tools and advocates for more complex experimental designs to better simulate real-world environmental stress conditions. (Sattar et al., 2024). Crop productivity must increase by 44% by 2050 to meet rising food demand.

Abiotic (drought, heat) and biotic (pests, diseases) stressors threaten yields. Drought can slash wheat yields by 21% and maize by 40%. Soil health is paramount, contributing up to 60% of crop yield. Sustainable practices and precision agriculture are key to building resilient systems (Hayat et al., 2025).

Table 5: Nutrient Management, Water Stress, and Biotic Interactions in Quinoa

Factor	Management/Response	Drought Resilience/WUE Impact	Pest & Disease Impact	References
Nitrogen (N)	60–100kg/ha, timely application	↑ Biomass, WUE, protein	Strengthens growth, resilience	(Afzal et al., 2023; Sun et al., 2025)
Selenium (Se)	6mg/L seed priming	↑ Growth, yield, WUE, cell integrity	Enhanced health, reduced stress impact	(Raza et al., 2024; Sun et al., 2025)
Biochar/organic	Soil amendment	↑ Water retention, yield	Improves soil health, plant vigor	(Condori-Ataupillco et al., 2025; Derbali et al., 2023)
Deficit Irrigation	40–80% ETc	↑ Water productivity (up to 67%)	Variable effect; careful management needed	(Dehghanian et al., 2024; Grenfell-Shaw & Tester, 2021; Kaur et al., 2022)
Water Stress	Rainfed/low input systems	Tolerant genotypes maintain yield	↑ Disease risk (mildew, pests) especially in stressed plants	(Jacobsen et al., 2003)
Balanced Nutrition	NPK + micronutrient management	↑ Root, Photosynth, Osmo protection	Reduces susceptibility, boosts immunity	(Dehghanian et al., 2024; Nanduri et al., 2019; Rao & Shahid, 2012)

3. BREEDING AND GENETIC IMPROVEMENT FOR ENHANCED DROUGHT RESISTANCE IN QUINOA

Breeding quinoa for improved drought resistance is a critical focus to secure its role as a climate-resilient crop. Recent advances integrate traditional breeding, molecular approaches and genomic technologies to identify drought-tolerant genotypes and accelerate the development of superior cultivars (Fig. 2).

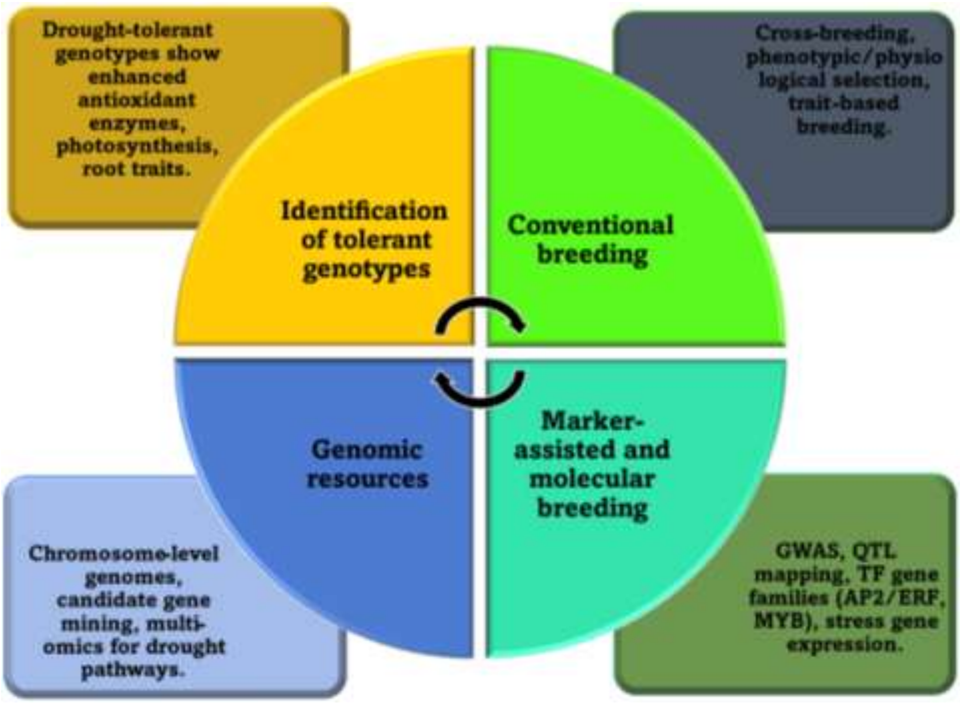

Fig. 2: Breeding and Genetic Improvement Components for Quinoa Drought Resistance.

3.1. Identifying Drought-Tolerant Genotypes and Landraces

Researchers have characterized diverse quinoa genotypes for drought tolerance by analyzing physiological, transcriptomic, and biochemical responses under water stress. For example, the drought-tolerant variety "Longly 1" showed higher antioxidant enzyme activities (SOD, POD, CAT), less photosynthetic damage, and distinct gene expression patterns under drought compared to susceptible types, confirming genotype-specific tolerance mechanisms.

To combat water scarcity and improve crop yields in arid regions, two strategies are proposed: breeding drought-tolerant crops using genes from wild relatives with modern tools like CRISPR, and introducing neglected, water-efficient crops into current agricultural systems. These methods aim to enhance food security (Rosero et al., 2020). A study on quinoa found drought at the flowering and seed-filling stages (DSFS) significantly reduces yield. Inoculation with plant growth-promoting rhizobacteria (PGPR), especially *Azospirillum brasilense*, improved growth, water use efficiency, and grain quality, effectively mitigating the negative impacts of drought (Aslam et al., 2020). A study on three quinoa cultivars (quinoa 1, rainbow, American) found varying water stress tolerances. Quinoa 1 proved most tolerant, followed by rainbow, then the American cultivar. All showed satisfactory yields under stress, linked to enhanced proline, glycine betaine and trehalose production. Genetic markers were identified to distinguish tolerant from sensitive cultivars (Khatab et al., 2022).

With climate change, crops face combined abiotic stresses (e.g., drought, heat), not just single ones. A crop's root system is crucial for stress response, yet how roots respond to these combined stresses is poorly understood. This review will explore root architecture, physiology, and molecular pathways to inform future crop breeding for enhanced resilience (Sánchez-Bermúdez et al., 2022). Landraces from arid Andean regions, including Salares and Altiplano ecotypes, provide valuable genetic resources for breeding because of their inherent adaptations such as extensive root systems, osmoprotectant accumulation and hormonal regulation enhancing drought resilience. Drylands, covering 47% of Earth, face climate change impacts like drought and soil degradation, threatening agricultural production. Plant genetic resources (PGR) in these areas, shaped by millennia of evolution, offer a solution. Conserving and utilizing these resources is crucial for developing climate-resilient agriculture and ensuring future food security (Paroda et al., 2024).

3.2. Conventional Breeding Approaches

Traditional breeding relies on cross-breeding of quinoa varieties exhibiting desirable traits like drought tolerance, early maturity, and yield stability. Selection has also utilized physio-morphological traits such as chlorophyll content, stomatal traits and root architecture. Molecular markers like RFLP and PCR have revolutionized crop breeding. Techniques such as FISH and QTL analysis enable efficient identification and transfer of genes for traits like drought and salt tolerance from wild relatives into cultivated crops, accelerating the development of resilient varieties (Quarrie, 1996). Due to their superior nutritional value, including being gluten-free, pseudocereals like amaranth and quinoa are becoming popular. These hardy, low-input crops are ideal for developing nations, but their potential is hindered by high saponin content and a lack of genetic improvement. Modern breeding technologies like CRISPR could accelerate the development of high-yielding, low-saponin varieties (Anuradha et al., 2023). To create improved quinoa varieties, a study analyzed six populations over three years in the Peruvian highlands. By assessing maturity and panicle traits, researchers identified three promising lines (HUA × KAN53, SAL × NCO46, and SAL × PAN171) that combined desirable traits like higher yield, earlier maturity, and reduced plant height, offering valuable data for future breeding programs (Lozano-Isla et al., 2023).

Quinoa, an ancient Andean crop, possesses exceptional nutrition and stress tolerance. Despite these qualities, its global adoption is limited. Recent breeding programs, supported by new molecular tools, and the recognition of the crop by the UN are expected to overcome genetic limitations and promote its wider cultivation (Zurita-Silva et al., 2014). Its high genetic diversity allows it to tolerate a wide range of conditions. However, its expansion outside the Andes is challenged by susceptibility to pests, diseases, and heat, requiring new breeding and agronomic practices (Gomez-Pando et al., 2019). Improving major crops by introducing genes from tolerant wild relatives, or by improving the agronomic performance of tolerant orphan crops like quinoa, are two ways to develop drought and salt-tolerant plants. This study proposes accelerating quinoa domestication by targeting and mutating specific domestication genes to make it a more nutritious, high-yielding crop (López-Marqués et al., 2020). Though conventional breeding has enhanced drought resistance to some extent, it is often slow and hampered by quinoa's self-pollinating nature and complex trait inheritance involving multiple genes and environmental interactions.

3.3. Molecular Breeding and Marker-Assisted Selection (MAS)

Molecular breeding uses molecular markers linked to drought-tolerance traits to speed up selection. Genome-wide association studies (GWAS) and genotyping-by-sequencing (GBS) approaches have identified thousands of markers associated with key agronomic and stress-related traits in quinoa (Rahman et al., 2024). Significant quantitative trait loci (QTLs) for drought response, yield, and seed quality have been mapped, enabling marker-assisted selection to introgress drought tolerance efficiently while maintaining yield and quality. A study of 72 quinoa genotypes identified traits and ISSR markers linked to high yield. The research found a strong correlation between panicle architecture and yield. This work provides a foundation for marker-assisted selection to develop superior, higher-yielding quinoa varieties (Habib et al., 2024). Marker-assisted breeding, or molecular breeding,

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ISSN: 2708-7182 (Print); ISSN: 2708-7190 (Online)
Open Access Journal

uses DNA markers to overcome the challenges of traditional phenotypic selection, especially for polygenic traits. Simple, cost-effective, and easy-to-use PCR-based markers like STS and SCARS are most suitable for breeders. Collaboration between breeders and molecular technologists is essential for effective implementation of this technology (Rajapakse, 2003). A study on quinoa varieties found Qing1 and Long4 had significantly higher yields (27.25% and 21.42% over control, respectively) and superior drought-resistance indicators (proline, CAT, soluble sugar, MDA). B-16 was ideal for functional foods due to its nutritional profile. Gong8 showed promise for both purposes (Li et al., 2025).

3.4. Genomic Resources and Applications in Drought Research

Chromosome-level genome assemblies of quinoa provide a foundational resource for functional genomics, enabling identification of drought-tolerance genes and their regulatory networks. Researchers sequenced high-quality, chromosome-level genomes for two high-quality highland quinoa lines, J075 and J100. These new genomic resources, with predicted protein-coding genes and repetitive sequences, will accelerate functional genomics research, helping to identify genes for environmental adaptation and domestication (Kobayashi et al., 2024). Drought severely impacts crops like maize, rice, and wheat, causing 30–90% yield losses. Plants cope via acclimatization and adaptation. Researchers are developing solutions using conventional methods like PGPB and modern techniques, including biochar and nanoparticles, to enhance water retention, nutrient uptake, and plant resilience in water-scarce environments (Khan et al., 2025). A study of 60 quinoa accessions found high genetic diversity, particularly in grain saponin and protein content. Researchers identified informative microsatellite (SSR) markers and used association studies to link these markers to important agronomic traits. The highest number of significant marker-trait associations (MTAs) were found for grain yield and 1000-grain weight (Souri Laki et al., 2024).

Drought severely limits wheat yield due to its complex genetic nature. To combat this, researchers are using wide hybridization with wild relatives and modern techniques like marker-assisted selection (MAS), QTL mapping, and OMICS technologies. These efforts, combined with transgenic and genome editing systems, aim to identify and utilize key genes and signaling molecules to enhance drought tolerance (Budak et al., 2015). To understand drought resistance in qingke, a study compared drought-sensitive (D) and drought-resistant (XL) varieties. The resistant type showed metabolic changes, including increased flavonoid and anthocyanin production, which enhanced tolerance. A specific gene, HVUL7H11410, was identified for its role in flavonoid glycosylation and drought resistance (Xu et al., 2021).

4. FUTURE CHALLENGES IN QUINOA CULTIVATION

4.1. Challenges in Quinoa Irrigation and Future Perspectives Center Around Several Interlinked Issues

Quinoa ecotypes from different Andean biogeographical regions (e.g., Inter-Andean valleys, highlands, salares, and coastal-lowlands) exhibit significant physiological and morphological variation affecting their water needs and drought tolerance. Research shows that water availability greatly impacts growth and yield, with low water supply drastically reducing plant height, biomass, and grain yield even in drought-tolerant genotypes. However, comprehensive, location- and ecotype-specific irrigation recommendations are scarce, complicating optimal water management. This gap calls for tailored protocols that consider genotype-environment interactions (Maliro & Njala, 2019). In Chile, a biodiversity hotspot, quinoa is a "lighthouse crop" with high genetic diversity. Nearly lost after Spanish colonization, it's now grown by small-scale farmers. Its unique traits make it crucial for promoting ecological agriculture, healthier nutrition, and equitable markets, as recognized by the UN (Bazile et al., 2014). A study on 99 quinoa genotypes in Chile found that drought reduced yield by 74%, but some genotypes still produced over 100 g m-2 with minimal rainfall. High yield and resilience under drought were linked to early maturity, high harvest index (HI), and thousand-grain weight (TKW) (del Pozo et al., 2023).

While quinoa is drought tolerant, higher and stable yields require adequate water supply. Studies demonstrate quinoa's yield potential increases substantially under optimal irrigation compared to water-limited conditions (Fig. 3). Salinity poses a significant threat to global food security, with climate change exacerbating the issue. Quinoa, a salt-tolerant and nutritious crop, could improve saline land productivity. A Moroccan study on five quinoa cultivars found that salinity and cultivar type significantly impacted yield. ICBA-Q5 yielded the most (2.17 t ha^{-1}) and INIA-420 Negra the least (0.33 t ha^{-1}), with late sowing possibly exacerbating heat stress (Abidi et al., 2022). Quinoa's adaptability to drought is due to diverse ecotypes from contrasting environments. It copes with water stress through physiological and morphological changes, affecting processes like photosynthesis and root growth. This makes quinoa a valuable crop for adapting to climate change and a source of genes for biotechnological applications (Zurita Silva et al., 2015).

In the Southern Bolivian Altiplano, deficit irrigation (applying less water than full crop water requirements) has been economically evaluated at the farm level using a hydro-economic model. Results showed that irrigation

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ISSN: 2708-7182 (Print); ISSN: 2708-7190 (Online)
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significantly increases quinoa yields and farmer profits compared to rainfed conditions across various climate scenarios (wet to very dry years). Maximum profit was usually achieved with intermediate levels of applied irrigation water—below what would produce the absolute maximum yield. This indicates water-saving deficit irrigation can enhance economic returns sustainably (Cusicanqui et al., 2013). Adopting deficit irrigation for maize, wheat, and sunflower in Southern Portugal is often not economically viable due to low irrigation system performance and high-water use. However, improving irrigation performance could make deficit irrigation feasible, especially for maize and wheat, if commodity prices remain high and water costs don't rise significantly. For sunflower, improved performance and high prices make it an attractive option, even under water restrictions (Rodrigues & Pereira, 2009).

In China's Hetao Irrigation District, a study on maize irrigation found drip irrigation at -30 kPa to be the most effective, boosting yield by 15% and profit by 23%, while cutting water use by 57%. If drip irrigation isn't possible, a 360-mm furrow irrigation is a viable alternative, saving 31% of water with comparable yield and profit (Zhang et al., 2021). While perceived as stress-tolerant, quinoa's yield is negatively impacted by drought, similar to maize and rice. Temperature changes don't affect any crop's yield in the studied region. Quinoa, along with major food crops, shows an upward yield trend, with a non-linear increase in recent decades (Geleyn). A study on quinoa's economic viability suggests it can be highly profitable, with an estimated net profit of up to AED 6,059 per hectare under a "most-likely" scenario. Monte Carlo simulations revealed a potential average net gain of AED 8,265 per hectare, with minimal risk of negative returns, emphasizing the crop's strong economic potential (Ahmadzai, 2020). An analysis of drought in Seoul, Korea, shows a future trend of fewer mild droughts but more frequent and longer severe/extreme droughts. Climate models (GCMs) predict more severe drought conditions than historical data suggests. Among the models, the MRI model forecasts the most severe future drought scenarios for the region (Lee & Kim, 2013).

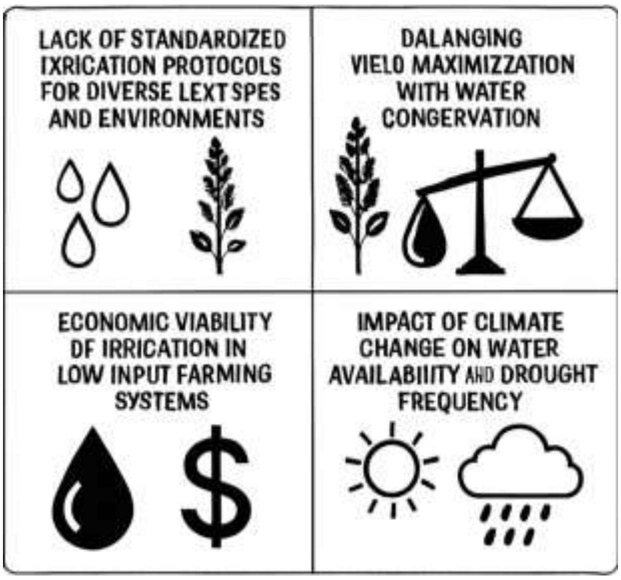

Fig. 3: Challenges and Future Perspectives.

4.2. Future Research Directions

4.2.1. Developing precision irrigation technologies for quinoa: A novel approach using deep learning-based instance segmentation (Mask R-CNN) has been developed for precise quinoa panicle detection and counting under different irrigation regimes (full and deficit irrigation). This technology enables accurate yield estimation and aids irrigation scheduling by monitoring crop growth and stress responses in real-time. The system can detect genotype-specific responses to water availability, which supports customized irrigation strategies for different quinoa varieties in water-limited environments (Fig. 4). This AI model demonstrated high accuracy and can potentially automate decision-making in irrigation management (El Akrouchi et al., 2025).

Smart sensors, integrated with IoT and AI, are transforming agriculture by providing real-time data on soil, crop, and environmental conditions. This allows for data-driven decisions to optimize resource use, boost yields, and promote sustainability. Innovations like drone-based and hyperspectral sensors are emerging. However, challenges like cost, data privacy, and interoperability must be addressed for widespread adoption to revolutionize farming practices and ensure global food security (Aarif KO et al., 2025). Plant phenomics uses high-throughput phenotyping (HTP), AI, and machine learning to analyze plant traits and environmental interactions in controlled environments. This approach optimizes crop yields and resource use by adjusting factors like lighting and nutrients. By integrating these technologies, phenomics helps create resilient, sustainable crops, ultimately enhancing global food security (Kaya, 2025).

Climate change threatens global food security by impairing crop reproduction. A multifaceted approach is needed to develop resilient crops. This involves using genetics, advanced breeding, and AI to understand and mitigate abiotic stress effects, ultimately creating climate-proof varieties and ensuring high productivity under unfavorable conditions (COST, 2025). Innovation is crucial for global food security. This review covers advancements from urban and regenerative farming to extreme-environment agriculture and biotechnology. It highlights AI's role in precision farming and emphasizes the importance of policy and community efforts to create a

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resilient, sustainable food system for the future (Silva et al., 2025). A study evaluated the AquaCrop model's accuracy for simulating quinoa growth. The model accurately simulated soil water content, yield, and biomass after being calibrated with region-specific data. Using the default global parameters resulted in significant inaccuracies, like a 60.8% overestimation of yield, highlighting the critical need to fine-tune the model for local conditions (Mirsafi et al., 2025). To enhance irrigation efficiency and sustainability in Peru's quinoa production, a study combined the AquaCrop model with the Crop Water Stress Index (CWSI). By calibrating the model with local data, researchers established an irrigation threshold of a CWSI of 0.44. This strategy saves 29% of water while still yielding 2.5 t ha^{-1}, demonstrating the effectiveness of integrating these technologies for optimizing water use in arid environments (Mendoza-Márquez et al., 2025).

Fig. 4: Checking the relationship between Drought and different irrigation techniques at the Agronomy Farm, University of Agriculture Faisalabad (Main-campus), Pakistan.

An IoT-multiagent precision irrigation system was developed for Colombia's Chicamocha and Firavitoba district. Intelligent agents autonomously manage irrigation for 5,911 fields, negotiating water use based on availability. This system successfully improved water use efficiency by correctly applying prescribed water amounts, offering a novel decision-making tool for water management (Jiménez et al., 2022). A study in Peru's Junín region found that conventional quinoa production has a global warming potential of 7.82 kg CO2-equivalent per kg of protein, comparable to other grain crops but far less than rice or animal products. However, the eco-efficiency of smallholder farms is low at 18.2%, primarily due to excessive mineral fertilizer use and a shift to mechanical threshing (Gamboa et al., 2020).

4.2.2. Integrating Physiological and Molecular Breeding for Multi-Stress Tolerance: Research on the quinoa cultivar 'Atlas' revealed that its immune responses, while similar to other plants, were slower and less intense. Interestingly, salt stress made the quinoa significantly more disease-resistant to the pathogen *Pseudomonas syringae*. This finding suggests that a salt-acclimation strategy could be a promising method for enhancing disease resistance in quinoa and other crops (Scrafton, 2023). A study identified 41 Universal Stress Protein (USP) genes in quinoa's genome. These CqUSP genes are crucial for helping the plant withstand abiotic stresses like drought and heat. The research characterized their structure, function, and regulatory mechanisms, highlighting their roles in defense, metabolism, and DNA repair, providing a foundation for future genetic research to enhance quinoa's stress tolerance (Imran et al., 2025). Salt stress significantly stunts quinoa seedling growth by increasing H_2O_2 levels, leading to cell membrane damage. In response, seedlings boost antioxidant enzymes (POD, SOD, GR, GPX) to mitigate this oxidative damage. Key genes and transcription factors involved in various metabolic pathways and hormone signaling were identified, providing a foundation for understanding quinoa's salt tolerance mechanisms (Li & Zhang, 2025).

The quinoa cultivar 'Hualhuas' is more salt-resistant than 'Real,' tolerating higher salinity levels. 'Hualhuas' exhibits more effective control over sodium accumulation, a better K^+/Na^+ ratio and greater photosynthetic water use efficiency, making it a promising candidate for cultivation in saline environments (Hussin et al., 2023). Both Chipaya and KU-2 quinoa cultivars showed greater salt tolerance than the model plant *Thellungiella halophila*. Quinoa's tolerance mechanisms involve a combination of salt exclusion and accumulation. High levels of the osmoprotectant trigonelline were found, and salt-stress-related genes showed constitutive leaf expression and upregulation in roots in response to stress (Morales et al., 2011). Variations in salt tolerance were observed among five highland quinoa cultivars. Salt tolerance was negatively associated with plant size, and not correlated with seed germination. Salt stress increased organic solutes, Na^+, and K^+, but decreased the K^+/Na^+ ratio. Salt tolerance was primarily conferred by leaf osmoregulation, ion homeostasis, and K^+/Na^+ ratio, which can be a key index for breeding new cultivars (Cai & Gao, 2020).

Plants cope with drought through various processes. Molecular and genomic analyses have identified many drought-inducible genes and transcription factors in plants like Arabidopsis and rice. These genes function in the initial stress response and in establishing stress tolerance. Genetic engineering of these genes has successfully enhanced dehydration stress tolerance in transgenic Arabidopsis (Shinozaki & Yamaguchi-Shinozaki, 2007). Identification of sodium/hydrogen antiporter (NHX) genes, universal stress protein (USP) families, and dehydrins highlights genes involved in ion sequestration, reactive oxygen species (ROS) scavenging, and molecular chaperoning as prime targets for genetic improvement to enhance stress tolerance (Santhoshi et al., 2025).

Using gene network analysis, a common gene module of 561 genes and 8863 edges was identified across seven stress-related diseases. This module, which significantly overlaps with chronic stress genes, contains 36 hub genes and is enriched in 190 functional clusters. The findings provide insight into shared mechanisms of stress-induced diseases and suggest new research targets (Guo et al., 2015). Thirty-four non-redundant CNGC genes were identified in quinoa, whose expansion was driven by gene duplication. These genes show distinct expression patterns under salt and heat stress, especially in roots. They likely interact with ROS-related proteins and kinases, participating in ion transport and calcium signaling. This research provides a basis for understanding quinoa's stress adaptation and for future crop improvement programs (Zhang et al., 2023). Multi-omics approaches, including genomics, transcriptomics, proteomics, and metabolomics, are used to understand drought stress in rice. These methods identify and manipulate drought-tolerant genes. By stacking these genes, multi-omics accelerates the development of drought-resistant rice, a crucial strategy for combating yield loss (Roy et al., 2025). Through integrated analysis, key synthases, metabolites, and transcription factors (TFs) were identified. Silencing CqMYB4 and CqbHLH216 TFs significantly reduced flavonoid content, suggesting they regulate flavonoid biosynthesis, enhancing stress resilience (Wang et al., 2025).

4.2.3. Recent Long-Term Field Studies on Drought and Irrigation in Quinoa: The study investigated quinoa's physiological response to drought and planting methods. The in-furrow planting method (P3) and 75% water requirements (WR) (I2) was the optimal combination, balancing high yields and water efficiency (Table 6). This method resulted in high protein yields and minimal reduction in essential plant characteristics, while maintaining a high Leaf Area Index (LAI) and photosynthetic rate (Mirsafi et al., 2024). A two-year study on quinoa in Iran found that applying 15 tons per hectare of vermicompost resulted in the highest soil nutrient levels (phosphorus, ammonium, nitrate, and potassium) and the highest seed yield (1784.01 kg ha^{-1}). This demonstrates that vermicompost improves soil properties, moisture retention, and mitigates drought stress (Sanandaji et al., 2024). Droughts and agriculture intensify water scarcity on the Andean Altiplano. A study using remote sensing data validates this by showing that increased quinoa farming since 2001 corresponds with decreases in vegetation health and total water storage, indicating agriculture is a significant contributor to the region's desertification (Satgé et al., 2019).

A dissertation on insular Caribbean drought found a strong link between the Atlantic Meridional Mode (AMM) and drought events, with the Lesser Antilles experiencing more intense and frequent droughts. Future projections indicate that by the mid-21st century, smaller islands like St. Croix will face significant water deficits and reduced crop suitability, while in larger islands like Puerto Rico, the southern region's agriculture will be most impacted. In two years of trials in Northwest China, researchers studied the effect of four irrigation levels on quinoa yield. While growth indicators peaked at the highest irrigation level, water productivity was highest with less water. The study concluded that strategic irrigation—reducing water in early growth and increasing it from heading to grain filling—could optimize quinoa yield while conserving water (Awa et al., 2025).

4.2.4. Exploring the role of beneficial microbes (e.g., mycorrhizae) in enhancing drought tolerance: Beneficial microbes, especially arbuscular mycorrhizal fungi (AMF), have emerged as crucial allies in enhancing drought tolerance in quinoa by improving physiological, biochemical, and metabolic plant responses under water stress. Recent research demonstrates these positive effects through multiple mechanisms, including improved nutrient uptake, antioxidative defense, water retention, and soil health, supporting sustainable quinoa cultivation in drought-prone environments.

Modern agriculture faces challenges from drought (Table 7), but a new study shows a solution for quinoa. Applying native microbial biostimulants and compost significantly improved quinoa's drought tolerance. This method not only increased grain yield by up to 97% under drought stress but also enhanced the grain's nutritional

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quality and improved soil fertility, offering a sustainable way to increase food production (Toubali et al., 2022). A study on quinoa under water stress found that using native arbuscular mycorrhizal fungi (AMF) and organic compost improved plant tolerance. The treatments increased protein content and enhanced levels of beneficial phenolic compounds in the seeds. This suggests that these biostimulants are a viable strategy for improving quinoa's nutritional value and resilience in water-stressed environments (Benaffari et al., 2024).

Table 6: Selected Long-term Field Studies on Quinoa Drought and Irrigation (2020–2025)

Study Focus	Features / Findings	Reference
Irrigation levels and planting methods	Deficit irrigation (75%) + in-furrow planting optimize physiological responses and yield over multiple seasons	(Mirsafi et al., 2024)
Vermicompost + irrigation over 2 years	Organic amendments improve soil, mitigate drought effects, enhance yield and soil moisture under varying irrigation	(Sanandaji et al., 2024)
AquaCrop modeling for irrigation optimization	Simulation of soil water and yield under different irrigation; supports precision irrigation scheduling	(Mendoza-Márquez et al., 2025)
Regulated deficit irrigation and yield stability	Multi-season deficit irrigation saves water with minimal yield loss; improves water productivity	(Barrett et al., 2022)
Soil quality after repeated irrigation	Long-term irrigation affects soil nutrients and water-holding capacity; organic amendments are vital	(Fadl et al., 2024; Zheng et al., 2024)
Economic water productivity	Intermediate irrigation improves profit and water-use efficiency in smallholder systems	(Dutta et al., 2020; Haileslassie et al., 2016)
Crop water stress index thresholds	Defining CWSI for irrigation scheduling to reduce drought impact over years	(Fattahi et al., 2018; O'Shaughnessy et al., 2012)
Multi-location resilience and adaptability	Coordinated field trials reveal genotype-environment interaction affecting yield and stress response	(Braun et al., 2010; Wondaferew et al., 2024)
Integrated water and nutrient management	Multi-season fertilization and irrigation synergy enhances drought tolerance and yield stability	(Nhantumbo et al., 2021; OK, 2025)
Photosynthesis and gas exchange dynamics	Effects of irrigation and planting method on physiological traits over consecutive seasons	(Ahmad et al., 2020; Hua et al., 2021; Ninou et al., 2013)

Table 7: Role of Beneficial Microbes (AMF) in Enhancing Drought Tolerance in Quinoa

Key Role/Effect	Findings
Improved growth, yield, and physiology	Up to 97% grain dry weight improvement; restored antioxidative enzyme functions
Enhanced nutrient uptake (P, N)	Increased macronutrient content in grains and improved soil fertility
Altered metabolite profiles	Higher antioxidant phenols and flavonoids contributing to drought resilience
Maintained membrane integrity and water status	Reduced ROS, improved osmotic adjustment
Increased photosynthesis and stomatal conductance	Better chlorophyll content and biomass under drought
Soil structure and moisture retention	Improved soil aggregation and water holding capacity under drought
Regulation of drought resistance genes	Enhanced expression of antioxidative and osmolyte synthesis genes
Synergistic effects with compost and microbes	Combined treatments outperform solo applications
Sustainable soil and water management	Improved post-harvest soil organic matter and phosphorus under water stress
Validation in other crops	Similar AMF benefits confirmed in soybean and Populus spp.

Sources: (Benaffari et al., 2024; Chen et al., 2022; Gujjar et al., 2020; Kallenbach et al., 2019; Sun & Lu, 2014; Tang et al., 2022; Toubali et al., 2022; Zhang et al., 2023; Zhao et al., 2019).

Arbuscular mycorrhizal fungi (AMF) are crucial for mitigating drought stress in plants. They improve plant growth, water relations, and nutrient uptake, while also enhancing photosynthetic efficiency and antioxidant activities. By protecting against oxidative stress, AMF significantly increases plant tolerance to drought. The review highlights AMF's mechanisms for drought tolerance, its role in improving nitrogen use efficiency, and identifies future research gaps (Tang et al., 2022).

5. CONCLUSION

Quinoa, a climate-resilient pseudo-cereal originating from the Andes, offers a vital solution to global food security amid rising drought and climate challenges. Its inherent drought tolerance, extensive genetic diversity, and adaptability to marginal soils and salinity enable stable yields even under water-limited conditions. Recent research demonstrates that deficit irrigation, nutrient management (e.g., nitrogen and selenium application), and beneficial microbes (arbuscular mycorrhizal fungi) substantially enhance quinoa's drought resilience and water use efficiency. Molecular breeding and genomics facilitate the identification of drought-tolerant genotypes, while precision irrigation technologies, such as AI-driven phenotyping and IoT-based systems, promise to optimize water management. Though challenges remain in standardizing irrigation protocols and ensuring economic viability for smallholders, integrating genotype-specific water management with sustainable agronomic practices can bridge these gaps. Future research directions prioritize developing precision irrigation, molecular breeding for multi-stress tolerance, and leveraging beneficial microbes, collectively ensuring quinoa's expansion as a resilient, nutritious crop supporting sustainable agriculture and food security worldwide.

DECLARATIONS

Funding: This study did not get any financial support from any agency/institution.

Conflict of Interest: The authors declare no conflict of interest.

Data Availability: All the data collected is present inside the article.

Ethics Statement: Not Applicable.

Author's Contribution: AA, MA, DH and TT wrote the initial draft of the manuscript. QA and MKH, AH made all necessary corrections and carried out final editing of the manuscript. FY and AI proofread the manuscript. All authors have reviewed and approved the final version of the manuscript for publication.

Generative AI Statements: The authors declare that no Gen AI/DeepSeek was used in the writing/creation of this manuscript.

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Citation: Akram A, Abdullah M, Haider D, Tariq T, Ali Q, Hayat MK, Haseeb A, Yasin F and Iqbal A, 2025. Thriving in adversity: quinoa's response to drought and the promise of optimized watering. Agrobiological Records 21: 78-98 https://doi.org/10.47278/journal.abr/2025.035

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