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Review Article

Physiological and growth response of Quinoa under changing climatic conditions: A review

Muhammad Daod Khan[1], Sher Afghan[1], Alia Ijaz[2], Muhammad Saud Khan[3], Asif Mehmood[1], Amina Rashid[1], Raza Mustafa[4], Muhammad Usman Arshad[1], Muhammad Mujahid[1], Rizwan Abid[1], Muhammad Sajjad[1]
[1]*Department of Agronomy, University of Agriculture, Faisalabad, 38000, Pakistan.*
[2]*Department of Botany, Government College University, Faisalabad. 38000, Pakistan.*
[3]*College of Life Science and Technology Tarim University Xinjiang Alaer China.*
[4]*University of Poonch Rawalakot Azad Jammu & Kashmir.*

ABSTRACT

The global population is increasing, while the amount of arable land is decreasing due to desertification and salinization, both of which are primarily caused by human activities, such as climate change. Global climate scenarios and food security will be fundamentally altered by increased temperatures; the entire ecosystem will be altered. This review examines the remarkable resilience of *Chenopodium quinoa* Willd. can provide or support ecosystem services in a sustainable approach to ameliorating impacts such as famine. In contrast to the conventional food staples, quinoa exhibits remarkable resilience to abiotic stresses and is a highly nutritious crop with a distinct nutritional profile. As such, it holds potential importance for ensuring food security and nutritional adequacy. With regard to the growing worldwide population, the consequences of climate change, desalination, phytoremediation, nutrient deficit, and poverty alleviation, this crop has the ability to improve global conditions.

Keywords: Quinoa; physiology; growth; climate change; agro-climatic.

INTRODUCTION

Quinoa (*Chenopodium quinoa* Willd.), a member of the Amaranthaceae family is mainly grown in dry areas of the Andes in South America and has a wide tolerable elevation range of 0-4 km. It also displays tolerable conditions to myriad climates which include cold, temperate and warm (Angeli et al., 2020). Quinoa is a broad-leafed plant with starchy dicotyledonous seeds and is not technically a cereal (Fig. 1). It is more accurate to say it falls into the classification of pseudo-cereal crops.

The quinoa plant (*Chenopodium quinoa* Willd.) is one of the most important agricultural and globally significant food-related plants that is currently being examined because of the impact of environmental temperature on its growth and development (Sowinski et al., 2024). The consequences of a changing climate are currently endangering food security in several parts of the world and it is anticipated that the significant temperature changes that occur throughout the day and night will have a greater impact on the production of quinoa (Hinojosa et al., 2019).

Quinoa is now a widely grown commercial crop in the world. While it took several centuries for previously introduced crops such as potatoes and soybeans to gain widespread acceptance and appeal, it has taken only 30 years for quinoa to achieve an almost superior standing on a worldwide scale (Dehghanian et al., 2024). Quinoa's rich mineral content and exceptional resistance to abiotic stressors and poor agricultural practices have garnered it attention on a global scale. It has transformed from a local crop that was hardly eaten to a highly significant pseudo grain. Due to the increasing popularity of quinoa consumption worldwide, export

Correspondence
Muhammad Sajjad
muhammadsajjaduaf@gmail.com

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Figure 1. Quinoa plants leaves.

levels have surpassed USD 70 million in Bolivia and USD 25 million in Peru (Bazile, 2023). *Chenopodium quinoa* is a common native grain of the Andes. It falls under the pseudocereal category. Given their comparable macronutrient makeup to cereals, pseudo cereals are frequently categorized as bread cereals (Ijaz et al., 2023a; Ijaz et al., 2023b). The three most well-known pseudo cereals are quinoa, amaranth, and buckwheat. "Any of several plants that aren't related to the grass family but yield seeds and fruits that are used as flour for bread and other staples" is how the dictionary defines the term (Fig. 2). They are currently becoming more popular as gluten-free substitutes for grains, according to the health grain consortium.

Figure 2. Three varieties of quinoa grown at Chakara site, University of Agriculture, Faisalabad.

Morphology

Quinoa was once referred to as "the mother grain" and has a well-established outstanding nutritional quality. With a cultivation history spanning about 7000 years, quinoa is one of the most ancient crops in the Andes (Anand et al., 2021). Quinoa plants have thick, tall, woody stalks and taproot systems (Fig. 3). They can grow to a height of 0.3 to 3 m and are available in a variety of colors including white, yellow, pink and darker shades of red, purple and black. Its polymorphic leaves begin life as green and eventually change to crimson, purple or yellow as they mature. The diameter of the seed varies between 0.28 and 2.1 cm and its colors may be pink, black, red, orange, white or yellow (Jaikishun et al., 2019).

Figure 3. Root system of Quinoa.

Global cultivated area

Between 2000 and 2019, there has been a notable increase in the cultivated land area, mostly in Bolivia (from 35,690 to 64,789 ha^{-1}) and Peru (from 27,578 to 37,625 ha^{-1}). The United States (53.1%), Canada (15.0%), France (8.0%), the Netherlands (6.1%), Belgium (4.5%), Germany (4%) and the United Kingdom (2%) are the main importers of their harvests (Jaikishun et al., 2019). Bolivia and Peru continue to be the world's leading producers of quinoa. In 2013, 45,000 ha of quinoa were grown in Peru and 75,000 ha in Bolivia. More than 85% of the world's quinoa is produced in these two nations with the remaining 15%-20% coming from Ecuador, the United States, China, Chile, France, Argentina and Canada combined (Bazile, 2023). The United Nations General Assembly declared 2013 the International Year of Quinoa (IYQ).

Climate change is a threat

Given the consequences of global warming and population expansion, quinoa is a versatile pseudo-cereal crop with tremendous potential to meet the increasing demands for food and alleviate poverty. It is considered a crop resistant to climatic change and comes from the Andes. Due to its extraordinary agronomic adaptations to many adverse climatic circumstances, quinoa is a very nutritious, gluten-free seed crop that may be grown in regions that are vulnerable to climate change. Quinoa grows and adapts to even the harshest and most merciless climates including frost, high salinity and drought (Dehghanian et al., 2024). Under rapidly changing climate conditions, this crop has the potential to contribute to a sustainable global food supply while reducing pressure on arable land (Sajjad et al., 2024; Afzal et al., 2023).

Climate change is likely to have substantial socioeconomic consequences for the environment and the global population due to impacts on crop plant yield and development. With the global population expected to advance to over 9.8 billion in the mid-21st century and 11.2 billion in the 22nd century, agricultural outputs will need to expand exponentially to accommodate the population boom (Bilalis et al., 2019). The different effects of climate change upon daily happenings have yielded several modifications in not only plant growth and development but even more so, for the agricultural sector it is troubling that environmental stress greatly influences plant behavior and global agricultural production systems. To deal with these effects both public and private organizations have started developing strategic plans that will enable the addition and improvement of plant species that are abler to withstand unfavorable agricultural and environmental circumstances, ultimately increasing the quantity and quality of food that is available to humans (Prajapati et al., 2024). We are enhancing global food availability while observing changes in the phenological and physiological traits of major crops. Studies suggest that extreme temperatures, drought, salinity and flooding may threaten food production and global food security (Dehghanian et al., 2024).

Nutritional value

Quinoa and amaranth are regarded as "one of the crops of the 21st century" due to their resistance and nutrition. They will be crucial for supplying sustainable food under unfavorable climatic conditions brought on by climate change scenarios (Jaikishun et al., 2019). Food and Agricultural Organization (FAO) and the World Health Organization (WHO) declared that quinoa is capable of meeting human body functioning needs as it contains all essential amino acids that a human body needs. Quinoa is a highly nutritious grain with exceptional protein quality, providing amino acids in amounts well above human dietary requirements including high levels of lysine, threonine and valine (Ali et al., 2025). Its dry matter contains 58-64% carbohydrates, balanced sugars and essential fatty acids that support health. Compared with cereals like rice, wheat, corn, oats and barley, quinoa offers greater protein, minerals and vitamins, particularly folic acid, carotene and vitamins C, A, E, and B complex (Chavan et al., 2025). A typical serving provides 222 calories, 8 g protein, 5 g fiber, 118 mg magnesium and 2.8 mg iron making it a functional food of high nutritional value.

Nutritionally, raw quinoa flour is rich in protein (14.02%), fat (5.13%), ash (3.83%) and key minerals such as Ca, Mg and Zn, while sprouting further enhances iron and fiber content. Overall, raw and sprouted quinoa retain higher nutrient levels than processed forms (Rana et al., 2019). Quinoa is a gluten-free grain with high-quality protein, a low glycemic index, unsaturated fatty acids, essential vitamins and minerals offering significant health benefits. Its carbon and water footprint is 30-60 times lower than meat, making it a highly sustainable food.

PHYSIOLOGICAL RESPONSES OF QUINOA TO CHANGING CLIMATIC CONDITIONS

Beginning in South America, quinoa (*Chenopodium quinoa*) is distinguished by its nutrition and high and remarkable ability to adapt to a varied array of edaphic-climatic situations. The plant's genetic variability is evident in its diverse physiological and phenological responses. The study set out to assess the proximal composition and physiological reaction of the grains to three different fertilization types at 2,875 meters above sea level. It has been noted that fertilization sources influence phenological and physiological behavior primarily leaf count, stem length and chlorophyll content but not yield (Jorfi et al., 2022). As a result of increased demographic pressure brought on by the world's population growth arable land is constantly disappearing. Since 1900, the measured temperature has increased by 0.6°C, and this increase is occurring faster than anticipated. The summer of 2022 was the driest and warmest on record in the Northern Hemisphere and the second warmest in Europe since the beginning of climatological records. Environmental change is a major factor reducing crop production particularly in low and middle-income regions. Rising CO_2 levels along with shifts in temperature and air conditions further threaten agricultural productivity (Mirsafi et al., 2024).

Temperature stress

The two abiotic stressors that have been studied the most in relation to quinoa are salinity and drought; research on other significant stressors like UV-B light irradiance, heavy metals, cold and heat is lacking. The erratic weather patterns observed over the past few decades have increased the prevalence of abiotic stress. Moreover, stressors are typically combinations of two or more. Exhaustive descriptions of quinoa's tolerance, current understanding of various abiotic stresses, a review of the plant's physiological reactions to these stressors and an account of recent developments in molecular tools that may help us comprehend underlying abiotic stresses tolerance of quinoa's mechanisms (Dehghanian et al., 2024).

Impact on photosynthesis and metabolic processes

Extreme heat stress events are occurring more frequently as climate change results and global warming which has plant productivity impact is negative. A complex physiological process that is sensitive to heat is photosynthesis. Heat stress affects CO_2 assimilation, photochemical reactions, chlorophyll biosynthesis and the turnover of D1 and D2 proteins thereby reducing photosynthetic efficiency. Heat stress damages chloroplasts and inactivates key proteins such as Rubisco activase, leading to redox imbalance, reduced photosynthetic efficiency and possible cell death (Sohaib et al., 2023). Organelles play a key role in signaling and responding to heat stress as Calvin cycle reactions and photochemical processes in the thylakoid lamellae and stroma of chloroplasts are highly vulnerable to heat-induced damage. Strategies to protect crops from heat-induced photochemical damage involve chloroplast responses, retrograde signaling and regulation of photosynthetic apparatus tolerance and sensitivity. Stress from high light and high temperature (HLHT) severely disrupts photosynthesis (Manaa et al., 2021). Developing photoautotrophs with tolerance to HLHT is difficult, as the molecular pathways governing this tolerance are complex and still not fully understood. By modifying cultivation conditions and genetic fidelity, researchers increased the mutation rate of

Synechococcus elongatus PCC 7942 threefold and isolated mutants with improved tolerance to high light and high temperature (HLHT). Genome analysis revealed that mutations in upstream non-coding regions enhanced expression of the shikimate kinase gene, and its overexpression in both *Synechococcus* and *Synechocystis* conferred greater HLHT resistance (Sun et al., 2023).

In a short-term (five-day) study conducted by Luo et al. (2023), three temperature regimes were tested during flowering and fruiting: control (18°C/28°C), sub-high (25°C/35°C) and high (30°C/40°C), along with five nitrogen levels (0-312.5 kg hm^2). Results showed that high-temperature stress reduced growth and quality, whereas sub-high temperature temporarily improved yield and nitrogen metabolism. Optimized nitrogen application enhanced tomato tolerance to heat stress. Similarly, in quinoa, moderate heat exposure has been reported to influence physiological and metabolic activities, where optimal nitrogen supplies improved photosynthetic efficiency, grain filling and stress tolerance under elevated temperatures (Khaliq et al., 2023).

Heat and cold stress responses in quinoa

Extreme weather events and climate variability are expected to occur more frequently in the future years, which will affect the consistent and secure production of food. Because of its high nutritional content and versatility, quinoa as a viable option for providing greater food security in a world with more fluctuating weather patterns. Quinoa can grow and is remarkably adaptable in a condition of wide range such as drought, heat, salinity, cold, soil, UV-B radiation and heavy metals. Quinoa research has mainly focused on salinity and drought adaptation, with their genetic diversity well characterized. (Dehghanian et al., 2024). Quinoa exposed to cold stress (-20 °C and 4 °C) before fermentation with *Lactobacillus plantarum* showed sharp increases in GABA content (1191% and 774%). As shown in Figure (4), quinoa flowers under control conditions (A) had normal growth, while those under high temperature (B) showed reduced distal axis length. Cold stress also caused surface defects in flour, disrupted -OH bonds, slowed protein degradation and reduced peak viscosity while overall enhancing GABA accumulation (Zhang et al., 2022).

A transcriptome comparison between cold-sensitive quinoa (CSQ5) and cold-resistant (CRQ64) revealed 6,432 unique genes and 55,389 novel isoforms. CRQ64 showed more differentially expressed genes and alternative splicing under cold stress, enriched in pathways related to ROS homeostasis, osmoregulation, phenylpropanoid biosynthesis and sucrose metabolism. Genes with peroxidase activity, 2,956 lncRNAs and 5,988 transcription factors were also identified as key components of the cold stress response (Zheng et al., 2022).

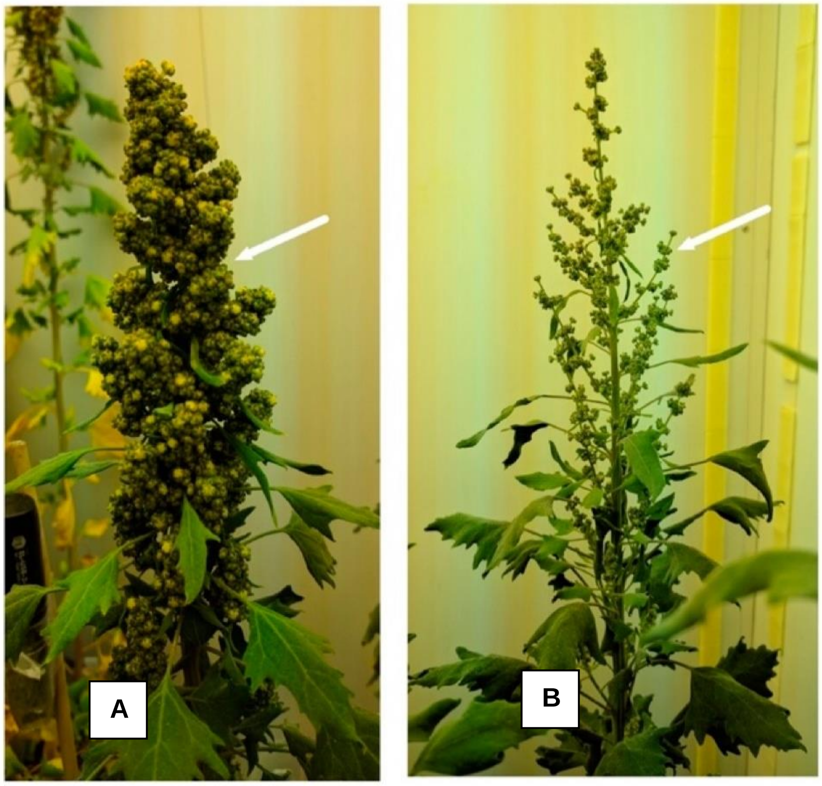

Figure 4. Effect of high temperature on the distal axis length of quinoa flowers. (A) Plant grown under controlled conditions (22/16 °C); (B) Plant exposed to high temperature (40/24 °C).

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Water stress

One of the primary abiotic causes of agronomic losses in the world is drought. Many approaches have been proposed to mitigate its effects including the use of plant growth-promoting bacteria (PGPBs), which have demonstrated resistance to abiotic stress. With emerging crops like quinoa, this feature has not received much attention despite its potential to help reduce food insecurity. The quinoa rhizosphere bacterial populations are shaped by the genotype, water environment and type of inoculant, which in turn affect plant performance (Badran et al., 2023). In order to address this, the importance of these parameters was defined using two distinct quinoa cultivars (with differing water stress tolerance), two water conditions (optimal and limiting) and two soil infusions. We identified distinct bacterial families that differ in terms of genotype. Numerous bacterial families were found, with variations observed in genotypes and water conditions. Water stress conditions enhanced the presence of some families (Akram et al., 2025). Quinoa root bacteria vary by cultivar and water response: F15 (water-sensitive) was enriched with Nocardioidaceae, while F16 (water-tolerant, higher polyphenols) had more Pseudomonadaceae, Burkholderiaceae and Sphingomonadaceae. This shows strong genotype environment effects and highlights quinoa as a potential source of PGPBs for drought conditions.

Mechanisms of water use efficiency in quinoa

Irrigation levels strongly influence quinoa performance. Mirsafi et al. (2024) proposed trials using 50%, 75% and 100% of plant water requirement (PWR) showed that severe drought reduced plant height by 31.8% and negatively affected 1000-seed weight and seed yield. Foliar application of GABA (10 mg L^{-1}) and vermicompost (5 t ha^{-1}) mitigated these effects, increasing the harvest index, seed yield, proline, sucrose and P and K concentrations as well as improving water use efficiency. Quinoa exhibits moderate salt tolerance (salinity threshold 4 dS m^{-1}) and shows sensitivity to drought (Ky = 1.55) but tolerance to salinity-induced stress (Ky = 0.47). Combined water and salinity stress indicates that the crop responds primarily to the most severe stressor, making irrigation and soil management critical for maintaining yield under multiple stress conditions (Sajjad et al., 2025a; Amin et al., 2023; Bouras et al., 2022) (Figure 5).

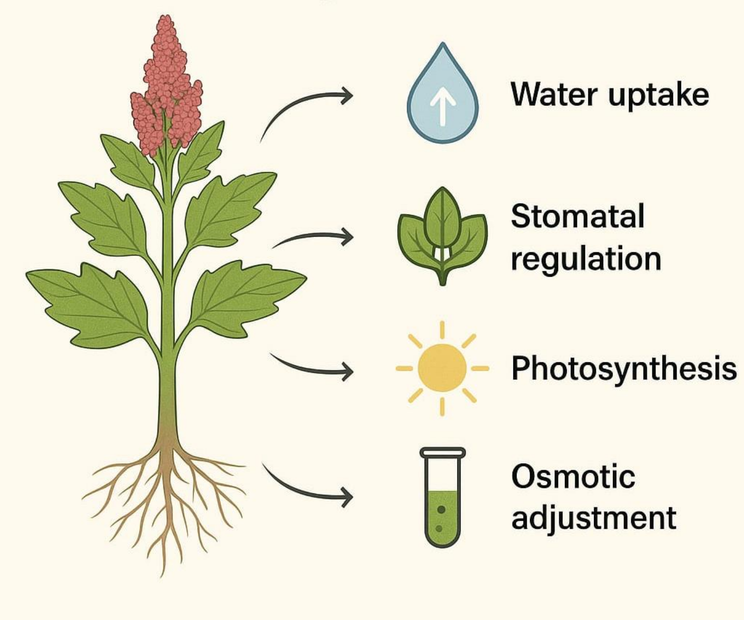

Figure 5. Water use efficiency in quinoa plant.

CO_2 concentrations

Quinoa's high nutritional value has caused its production to grow worldwide. Because of its resilience to environmental challenges, this crop can be grown in sustainable farming systems. There aren't many studies that look at how various agricultural management practices affect climate change. Measure soil greenhouse gas (GHG) emissions using the following metrics: yields and biomass of crops fertilized with conventional fertilizers (urea) and organic fertilizers (digestate) as well as carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) (Ahmad et al., 2023; Shakeel et al., 2021). The collective N_2O emission between control (0 kg N ha^{-1}), urea (50-100 kg N ha^{-1}) and digestate (50-100 kg N ha^{-1}). The digestate contained less than 100 kg N ha^{-1} and resulted in comparatively higher CO_2 emissions, reaching about 337.8 kg C ha^{-1}. The total amount of N_2O emissions between digestate (50-100 kg N ha^{-1}) and urea

(50-100 kg N ha^{-1}). In comparison to treatments with lower nitrogen (N) inputs, higher cumulative GHG emissions are reported under digestate (100 kg N ha^{-1}), CO_2 (337.8 kg C ha^{-1}) and 0.23 kg N ha^{-1} of N_2O. Therefore, study not only gives agricultural extension workers more knowledge to support sustainable quinoa production globally but it also brings up a discussion regarding the benefits and drawbacks of increased fertilization to improve yields (Ahmadzai, 2020).

Quinoa response to elevated atmospheric CO_2 levels

Quinoa Willd, (C3) and *Amaranthus retroflexus* L. (C4-NAD) two plants with different forms of photosynthesis, were studied for their thermal durability at short-term increased temperatures (35°C) under ambient concentrations (Rakhmankulova et al., 2023). The study assessed photosystem II (PSII) and photosystem I (PSI) activity, water content, proline levels, growth traits and malondialdehyde (MDA), along with gas exchange (CO_2 and H_2O) and the concentrations of key photosynthetic (Rubisco, PEPC) and photorespiratory (GDC) enzymes (Fig. 6). Under the same conditions, C4-type plants (*Amaranthus retroflexus*) showed higher transpiration rates, stronger PSI activity, greater apparent photosynthesis and increased dry biomass compared to C3-type plants (*Chenopodium quinoa*), while maintaining lower proline levels (Rakhmankulova et al., 2023). However, elevated temperature negatively affected both types, reducing stomatal function, apparent photosynthesis and transpiration (Figure 6).

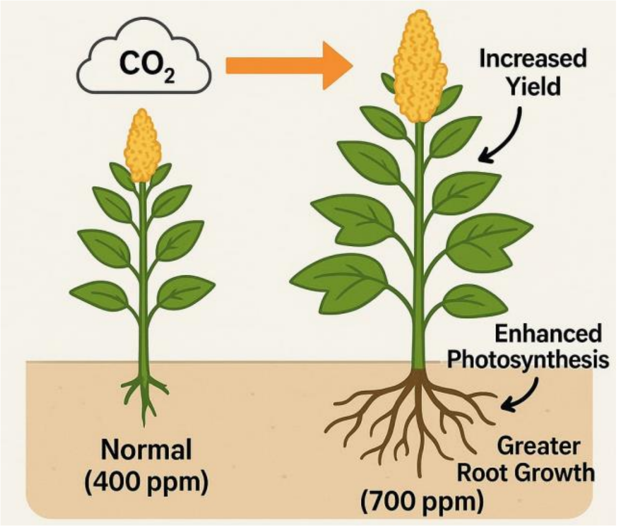

Figure 6**.** Response of quinoa plant against elevated atmospheric CO_2 levels.

GROWTH RESPONSE OF QUINOA TO CHANGING CLIMATIC CONDITIONS

Quinoa a key Andean crop is valued for its genetic diversity, resilience and ability to thrive in marginal soils, making it suitable for rehabilitating degraded lands. In field trials, Oustani et al. (2023) found genotype to be the main factor influencing traits such as yield, protein, saponin content and maturity. Q102 showed the highest yield (2.87 t/ha) and protein (16.7 g/100 g DM), maturing in 149 days. Giza1 had the lowest yield but shortest maturity (139 days) and lowest saponin (0.62 g/100 g DM) while Santa Maria matured latest (164 days) with the highest saponin (1.92 g/100 g DM) and largest grain size (2.68 g TGW). These findings underscore quinoa's potential for dryland agriculture in arid North Africa (Figure 7).

Phenological changes

Crop yield circumstances are rapidly deteriorating due to climatic changes. For example, it is predicted that most regions of the world will see a rise in salinization and aridity. It is therefore necessary to find new stress-tolerant genotypes and species with employing them in agronomy going forward (Afzal et al., 2023). Although they exist, stress-tolerant organisms are genuinely ignored and misused. Numerous research has made use of crop simulation models including those that choose the right cultivar, figure out when to plant, and forecast how variety and climate change will affect growth.

Flowering and seed development under an altered climate

Unfavorable climate during flowering can drastically reduce crop yields and disrupt plant-pollinator interactions, largely by altering flower metabolism. This perspective highlights the impacts of climatic stressors on floral traits, including color, fragrance, nectar production and gamete development that can impact ecosystem health and the reproductive fitness of self- and cross-pollinating species (Mirsafi et al., 2024). We bring together the molecular basis of these responses, analyze publicly available gene expression studies discussing floral responses to heat and drought, and summarize metabolite measurements from flowers subject to heat stress, indicating that short experimental timeframes may underestimate the impact of heat on floral fitness. This work emphasizes the connection of climate, flower metabolism, and ecological consequences, a connection that can be lost in comparisons between geographic regions (Borghi et al., 2019).

The timing of flowering affects flowering quantity and reproductive success in plants. Climate change can influence flowering timing, but the effects are species-specific. In P. saundersiana and P. fruticosa, warming affected the timing of first flowering, but not the duration of flowering or flowering productivity. Simulated snowstorms delay the timing of first flowering in P. saundersiana but had negligible effects on P. fruticosa. Later flowering increases flower yield in both species; this implies that early flowering alone is insufficient to increase reproduction, rather, the timing of the final flowering is important (Dorji et al., 2020).

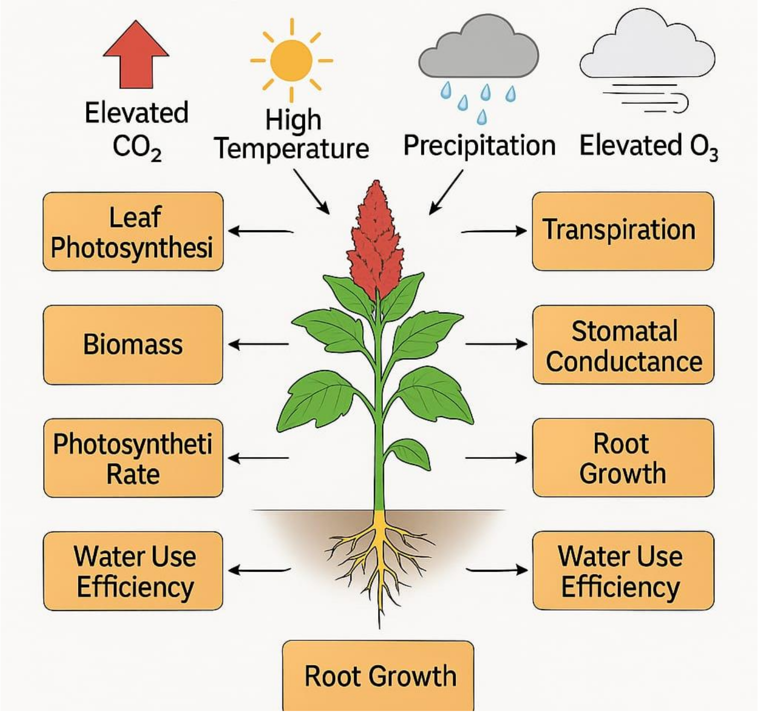

Figure 7. Quinoa response to changing climate

MOLECULAR AND GENETIC RESPONSES

Genetic diversity

Understanding genetic variability is critical for determining the conservation status of crop resources and locating new sources of diversity to enhance productivity and adaptability to geographical location (El-Harty et al., 2021). Molecular markers play an important role in conserving germplasm, and establishing core collections. Sequence-related amplified polymorphism (SRAP) markers are a type of marker developed by Robarts and Wolfe (2014), that target open reading frames and amplify the coding regions of DNA. They have been extensively used in studies related to plant systematics and biogeography. Robarts and Wolfe (2014), reviewed 171 studies, and noted the potential of SRAP markers as adaptable, biologically informative and friendly biological tools.

Examining quinoa varieties for climate resilience

A total of 32 quinoa genotypes were evaluated using Principal Coordinate Analysis (PCoA), which showed two distinct and separated subpopulations, which were mainly explained by the first three coordinates. The first coordinate effectively separated Population One and Population Two. This segregation was confirmed by STRUCTURE-based genetic clustering. Other studies have demonstrated similar significant genetic diversity in quinoa. Salazar et al. (2019) reported high levels of heterozygosity (He) among 84 Ecuadorian accessions using SSR markers. Delgado and Martin (2007) also reported higher He values in South American and 152 quinoa accessions respectively using microsatellite loci. Fuentes et al. (2009) reported that coastal genotypes in Chile had more alleles and higher Shannon index values than highland genotypes.

Differences in allele numbers and gene diversity among studies may occur based on experimental design, including germplasm size, geographic origin, and markers that are either dominant or codominant. Although low levels of variation can be found within species, Random Amplified Polymorphic DNA (RAPD)-based studies have shown high levels of polymorphism within C. quinoa and other related species. For example, Manugade et al. (2023) found a limited amount of difference between farmed and weedy populations, and suggested that the variation at the population level is more important due to gene flow, than differences between genotypes.

Breeding strategies for improved climate adaptation

The continuous trend of a warming climate is impacting global crop production as a function of modified temperature and precipitation patterns (Hasegawa et al, 2021). This trend is a reminder of the critical need for crops species which can sustain yields and tolerate changing environmental conditions. Quinoa, an important crop species, and native to the Andean highlands of Peru, is also under pressure from this trend. Farmers in the Andean highlands of Peru face climate challenges on a regular basis, such as hailstorms, droughts, and altered precipitation patterns (Flubacher et al., 2017). Any of which can be a serious threat to the smallholder farmers' food security and income.

To lessen the risk of adverse conditions, it is recommended to prioritize the quinoa lines that would have improved traits including yield, plant stature, and days to maturity. Quinoa genetic resources available in the Andes are remarkably diverse (Bazile et al. 2016), and these genetic resources hold great potential for plant breeders to use in developing better and new quinoa varieties for specific production regions. It will also be important to determine the preferences and needs of the smallholder farmers and other agricultural stakeholders while breeding quinoa (Gamboa et al. 2018). Farmers in highland Peru showed a distinct preference for quinoa types with larger grains, fewer saponins, greater yields, and earlier maturation.

Gene expression

Plant growth and development are largely regulated by transcription factors (TFs), proteins that control gene expression especially under stress conditions (Kim et al., 2021). TFs bind to cis-acting DNA regions to activate or repress target genes and are generally classified as activators or repressors (Ma and Zhong, 2025). Some TFs can function as both depending on their binding sites and interacting partners. Examples of such dual-role TFs include *Arabidopsis thaliana* PR-1, AtYY1 and potato PR-10a, all containing both activation and repression domains. Zinc-finger TFs are particularly important in plants, as their zinc-stabilized domains allow binding to DNA, RNA or proteins (Xuefen et al., 2022). They regulate responses to light, temperature, developmental cues and environmental stresses often through B-box zinc finger proteins. BBX TFs typically have one or two B-box domains at the N-terminus and some also possess a CCT domain at the C-terminus both contributing to their functional activity (Feng et al., 2021). These TFs are crucial for physiological and biochemical processes including photomorphogenesis, flowering induction, shading responses, carotenoid biosynthesis and tolerance to biotic and abiotic stresses.

Identifying key genes associated with climate resilience

Quinoa can grow in many different environments, from hot and rainy tropical areas to cold and dry regions. It thrives at altitudes from sea level up to 4,000 meters, with rainfall ranging from very high to extremely low and in soils with varying nutrients. To survive water scarcity, plants use two main strategies as avoiding stress or tolerating it (Sajjad et al., 2025b; Akram et al., 2024). Stress avoidance mechanisms help plants maintain a balance between water absorption and loss. These involve increased root growth, reduced water potential in tissues, and the collection of solutes to boost water uptake. The stomata close to increase water loss by evaporation. Stomata closure may also limit shoot growth and hasten leaf deterioration. Once water stress exceeds the limitations of avoidance mechanisms, stress tolerance mechanisms become operational to spare cells from suffering (Ain et al., 2023). These processes are focused on detoxifying reactive oxygen species (ROS) from cellular damage and accumulating protective proteins in tissues. Local quinoa diversity may reflect natural adaptation to specific soils or climates; however, again, the causes for variation in physiological responses remain unclear. Previous work (Hussin et al., 2023) had not clearly shown morph physiological adaptation. Quinoa is a suitable model plant as the five ecotypes have very diverse traits and stress tolerance.

CHALLENGES AND FUTURE DIRECTIONS

Quinoa faces several important problems including managing pests and illnesses, creating climate-resilient cultivars and preserving genetic variety. Stabilizing market prices and sustainably increasing production are important factors. Future research should concentrate on improving the nutritional value, comprehending mechanisms of adaptation, incorporating quinoa into a variety of food systems, promoting international cooperation, funding training and education, and supporting legislative initiatives.

Current challenges

Stand establishment is a critical stage in quinoa cultivation, as it affects both seed quality and yield. Farmers growing quinoa on marginal or saline soils often face challenges such as poor germination and low crop stands (Afzal et al., 2023). Quinoa seed germination and early seedling growth are highly sensitive to temperature and moisture. Optimal germination occurs between 20 and 35°C, declines below 15°C and above 45°C and ceases completely at 50°C. Low temperatures can also be fatal to embryos, halting germination. Quinoa seeds are small and sensitive to low soil moisture, creating challenges for researchers and farmers. Quinoa seeds are orthodox, meaning they are tolerant to drying to about 5% without losing viability; however, extended exposure to low moisture can hasten seed aging and modify the protein composition of seeds, diminishing their capacity to defend themselves from free radical damage during germination (Mirsafi et al., 2024). Despite being resilient, quinoa faces challenges in production, such as limited farmer knowledge, production costs, market instability affecting profitability, and limited quality seed and agro-technologies in some regions. To promote adaptive production and facilitate increased scaling, authorizing access to agro-technologies and quality seeds is essential to overcome economic and infrastructural constraints. Quinoa may be resilient but market, economic and potentially unavailable new adaptive varieties may contribute to barriers. It is important to develop supportive policies, plan research, and develop market access to reinforce quinoa's place in sustainable food systems. Addressing these barriers will ultimately support successful quinoa production and further develop its role in sustainable agricultural systems.

Limitations in existing Research

Quinoa research in the Andes began in the 1960s–1980s, focusing on plant breeding, nutrition, processing and germplasm collection. Political and economic factors caused uneven research efforts across the region (Afzal et al., 2023). Interest in quinoa grew in the 1990s with improved grain cleaning and the rise of the organic food industry, reaching popularity in the United States by the late 2000s. Since 2000, yields have increased, particularly in Ecuador and Peru. Genomic sequencing of 26 cultivars, completed in 2017, has supported breeding for stress tolerance and desirable traits. New programs outside the Andes focus on high-yielding, low-saponin and climate-resilient varieties but advanced breeding capacity in the Andes remains limited.

Gaps in understanding specific physiological and growth responses

Quinoa exhibits wide variation in how it responds to drought, with different genotypes showing unique strategies for coping with water stress. Several varieties actively grow during the early drought period due to strong root systems and high water absorption during drought. Other varieties may slow growth to persist and survive. Chlorophyll fluorescence is an effective method for determining drought responses in plants, but responses can differ between genotypes and studies need to be done under different conditions (Dehghanian et al., 2024). Root traits are very important for adaptation methods used during drought. Rapid, extensive branching and deep seed-root systems of quinoa an important trait when accessing deeper soil layers. These traits give quinoa potential as a resource for researchers examining plant growth, water use and physiological stress tolerance.

Future research directions

In the future, it would be helpful to understand the genetic basis for quinoa’s tolerance to abiotic stresses, and ultimately how these traits will impact grain quality. This information could be useful for breeders aiming to produce new varieties that can adapt to a broader range of environmental conditions, thereby fostering global expansion in quinoa growing conditions. Also, exploring crosses between quinoa and its wild relatives will enhance initiation of new genetic combinations that could show more prospective productivity under stressful agricultural conditions. Overall, quinoa is well-poised to serve as a crucial model system to study stress tolerance mechanisms and evaluate genes associated with better plant performance. Quinoa's incredible ability to tolerate stress creates exciting opportunities for agronomic and breeding applications. We will be able to further enhance productivity within variable climates through the combination of stress-resilient genotypes, better management of nutrients, and enhanced irrigation and sowing schedules. Additionally, breeding programs for tolerance traits for heat, drought and salt can further expand quinoa's opportunities as a more resilient crop in sustainable agriculture.

CONCLUSION

Studying quinoa's growth and physiological responses to changing climates allows us to better understand how this resilient crop interacts with environmental thresholds. Quinoa's most distinguishing attribute, the ability to adapt to waterlogged to arid soils, diverse climatic, elevational and ecological regions, makes it a prime example when discussing sustainable agriculture and global food security. Understanding quinoa's response to anticipated warming in climate, changing rainfall patterns and extremes are vital in the development of climate resilient varieties. Warmer temperatures, shifts in photoperiod, adjustments to rainfall duration and rainfall volume, are all directly linked to flowering and seed development, while increases in CO_2 concentration can further influence these responses and influence seed quality. Continued research and traditional plant breeding will allow us to develop quinoa cultivars that are more appropriately suited to warmer temperatures, changing rainfall patterns and extremes. Quinoa's ability to maintain yield under dry conditions is a further benefit, to decrease the risk of water stress in soils that receive ephemeral moisture. To fully harness quinoa’s potential, an integrated approach is needed that combines physiological research, breeding, sustainable farming practices and supportive policies. Studying quinoa is not just a scientific endeavor, but it is an avenue for promoting resilient food systems. Collaboration among scientists, farmers, policymakers and communities is vital for a secure and sustainable future.

AUTHOR’S CONTRIBUTION

Muhammad Daod Khan conceived the idea and compiled the manuscript. Sher Afghan, Alia Ijaz, Muhammad Saud Khan and Asif Mehmood contributed in collection of literature and write up. Amina Rashid, Raza Mustafa and Muhammad Usman Arshad reviewed and edited the paper. Muhammad Mujahid and Rizwan Abid supported the work through an extensive literature review and validation of the generated data. Muhammad Sajjad provided technical support, resources, and key input, led the conceptualization and supervision, prepared the manuscript, and approved the final version. All authors approved the manuscript.

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CONSENT FOR PUBLICATION

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CONFLICT OF INTERESTS

The authors declare there is no conflict of interest.

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