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Review Article

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Environmental factors shaping alpine plant adaptations

Pallavi Sati[1*], Sachin Dimri[2], Vijay Laxmi Trivedi[1] and M C Nautiyal[1]
[1]*High Altitude Plant Physiology Research Centre (HAPPRC), H.N.B. Garhwal University, Post Box: 14, Srinagar Garhwal 246174, Uttarakhand, India.*
[2]*Sai College of Pharmacy, 26, A- Rajpur road, Dehradun, Uttarakhand, India*
**Corresponding author e-mail: pallavisati45@gmail.com*
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ABSTRACT
Alpine ecosystems are distinct and demanding settings that are defined by severe climatic extremes, such as frigid temperatures, intense radiation, and restricted nutrition supply. The adaptations of alpine plants are finely tuned responses to the unique environmental challenges they face. By delving into the intricate interplay between temperature, UV radiation, soil conditions, and precipitation patterns, are valuable insights into the resilience of alpine ecosystems. Such knowledge is not only crucial for advancing ecological understanding but also for informing conservation and management strategies in the era of global environmental change. We have covered all the abiotic factors affecting plant growth and development in alpine and subalpine area in this mini review. It will be beneficial for researchers, industrialists, ecologists and agriculturists.
Keywords: Alpine and Subalpine plants, Climate change, Conservation, Elevated CO_2, Temperature.

INTRODUCTION

Alpine environments are characterized by harsh and extreme conditions, including low temperatures, high radiation, strong winds, and rocky or nutrient-poor soils. These challenging conditions have led to the evolution of unique adaptations in alpine plants. Alpine plants often face freezing temperatures (García-Plazaola *et al*., 2015). They have developed strategies such as small, compact growth forms, hairy or waxy surfaces to reduce heat loss, and the ability to photosynthesize at low temperatures. At higher altitudes, oxygen levels decrease, and atmospheric pressure drops. Plants have adaptations like increased stomatal density to enhance gas exchange, altered respiratory pathways, and enhanced energy efficiency (Rawat *et al*., 2014). High-altitude environments receive intense UV radiation due to reduced atmospheric filtration. Alpine plants may have specialized pigments, such as anthocyanins, and reflective surfaces to protect against UV damage (Bashyal, 2023). Snow cover can provide insulation during winter. Some alpine plants may have adaptations to capture and retain snow, creating a microenvironment that buffers against temperature extremes. Wind can be strong in alpine zones, and plants often adopt low, cushion-like growth forms to minimize exposure and reduce desiccation. Alpine plants face a short growing season. Many species have adapted by flowering and producing seeds early in the season to ensure reproductive success before the onset of harsh conditions (Linu *et al.* (2015). Alpine soils are often nutrient poor. Plants may develop extensive root systems, mycorrhizal associations, or adaptations for nutrient uptake efficiency to thrive in such conditions. Snow cover can provide insulation during winter. Some alpine plants may have adaptations to capture and retain snow, creating a microenvironment that buffers against temperature extremes. Human activities, such as tourism and climate change, can impact alpine ecosystems. Increased foot traffic can disturb fragile vegetation, and climate change may alter temperature and precipitation patterns, affecting plant distribution (Rawat *et al*., 2014). Limited vegetation and herbivore pressure can lead to the evolution of chemical defenses, such as secondary metabolites, to deter herbivores. We have tried to compile a short report on how environmental factors affecting the plants at higher elevation. Understanding how alpine plants adapt to extreme conditions helps in developing strategies for their conservation. As alpine ecosystems are particularly vulnerable to climate change and human disturbances, conservation efforts can benefit from insights into these adaptations (Rathore *et al*., 2018).

Different environmental factors and their effect

Nutrients - Previous research have shown that the development of alpine plant species is greatly influenced by the availability of nutrients. Plants at higher altitudes encounter limited nutrient availability, which may adversely impact their growth and development. *Aconitum carmichaeli* exhibited enhanced growth when treated with NPK, and a reduced biomass was found when exposed to low nutrient concentrations (Hou *et al.* 2006). In another study, plant height, tuber length, leaf number, aconitine and pseudoaconitine content increased when grown under nutrient rich environment in *Aconitum heterophyllum* and *Aconitum balfourii* (Bahuguna *et al*., 2013). *Rheum tanguticum* also affected by different level of nutrients (Shen *et al.* 2023). Root length, root fresh weigh and root diameter increased when fertilized with phosphorus and potassium. Multiple studies have shown that plants use various adaption mechanisms to deal with limited nutrition availability in alpine regions such as *Rhododendron anthopogon* (Rathore *et al.* 2018), *Saxifraga hostii* (Sedej *et al.* 2020), *Taxus wallichiana* (Adhikari *et al.* 2022) and *Aconitum naviculare* (Bashyal, 2023).

UV-radiation

In alpine regions, plants are exposed to elevated levels of ultraviolet (UV) radiation due to factors such as high altitude, clear skies, and reduced atmospheric filtration. UV radiation consists of UVA (320–400 nm), UVB (280–320 nm), and UVC (100–280 nm), with UVC mostly filtered by the Earth's atmosphere. According to Sedej *et al.* (2020), *Saxifraga hostii* exhibited high photochemical efficiency of photosystem II and stomatal conductance under near ambient UV radiation. However, leaf tissue thicknesses were not affected by different treatments of UV radiation. Their study concluded that, *S. hostii* leaves showed high absorption in the UV spectrum at higher altitudes, as shown by their optical properties. In *Kobresia humilis* enhanced UV-B radiation resulted in a significant increase of both leaf area and fresh weight. On the other hand, the enhanced UV-B radiation was associated with 2–3 days earlier flowering and a larger number of flowers per spikelet (Shi *et al*., 2022).

Elevated Carbon dioxide

Prior report demonstrated the effect of elevated CO_2 concentration on the growth, productivity, physiology, and various biochemical parameters of four alpine treelined herbaceous species, viz. *Acomastylis elata, Anaphalis nepalensis, Bistorta macrophylla,* and *Trillium govanianum* (Chandra *et al*., 2023). Their study revealed that, *Acomastylis elata* and *Anaphalis nepalensis* showed positive response to elevated CO_2 by increasing net photosynthesis, growth and productivity. On the other hand, *Bistorta macrophylla*, and *Trillium govanianum* decrease in net photosynthetic rate. The long-term effects of elevated CO_2 on *Picea abies*, *Pinus sylvestris* and *Betula pubescens* Ehrh. were examined in open-top chambers after a 4-year-long experiment. The *Picea abies* and *Betula pubescens* reduced biomass when exposed to elevated CO_2, while *Pinus sylvestris* increased biomass under elevate CO_2 (Vanhatalo *et al*., 2003). However, no effect observed in sever plant species such as *Vaccinium gaultherioides* and *Empetrum hermaphroditum* (Dawes *et al*., 2011). In Larix decidua Mill. and *Pinus mugo* net photosynthetic rate and stomatal conductance increased when exposed to elevated CO_2 while no changes observed in transpiration rate (Streit *et al*., 2014).

Temperature

Temperature plays a crucial role in the growth and metabolism of alpine plants, which are adapted to survive in harsh, cold environments at high altitudes. The impact of temperature on alpine plant physiology can be observed at various levels, including growth, photosynthesis, respiration, and overall metabolic processes. According to results from the study by Ma *et al.* (2015), *Potentilla saundersiana* modulates the root architecture and leaf phenotype to enhance adaptation to alpine environmental stress developed by low temperature and UV radiation. However no significant effects, also observed in alpine plants (*Soldanella alpina and Ranunculus glacialis*) when treated by low temperature (Sterb *et al*., 2003). Alpine regions typically have a short growing season due to low temperatures. Additionally, such climatic conditions can inhibit the growth of the alpine plant species. As earlier reported that increased temperature promoted the plant growth and development in *Ranunculus glacialis, Tussilago farfara, Rumex alpinus, Poa alpina* (Nagelmüller *et al*., 2017). Jeong *et al.* (2021) found that elevated temperatures may impact the growth and development of alpine plants when there is an adequate supply of nutrients. Their investigation revealed the adaptive reactions of *Primula farinosa* during its initial developmental phase in response to temperature. The findings indicated that plants had reduced survival rates but increased rosette size and leaf count in response to elevated temperatures. Another study revealed that, Temperature and precipitation are the main deterministic factors in species biomass change in *Betula* spp. and *Abies* spp (Usoltsev *et al*., 2022). Another study revealed that, net photosynthetic rate increased with decreasing temperature in *Abies koreana* (Woo *et al*., 2008) and decreased in *Abies faxoniana* (Yu *et al*., 2019). Prior studies also found that increased temperature had a substantial positive effect on the development of slow-growing alpine plant species (*Plantago euryphylla*) by increasing net photosynthesis and respiration rate (Atkin *et al*., 2006). However negative reports are also available in literature. Warmer temperatures during the growing season can extend the time available for alpine plants to complete their life cycles, including germination, flowering, and seed production. Rising global temperatures are inducing upward altitudinal migrations, altering the traditional distribution patterns of alpine vegetation (Li *et al*., 2013; Mietkiewicz *et al*., 2017). The tree line, indicative of the uppermost limit where trees can grow, is ascending, compelling alpine plant species to relocate to higher elevations.

Water availability

At higher elevations, water availability can be limited due to factors such as lower temperatures, reduced precipitation, and increased evaporation rates. Alpine plants often need to cope with scarcity by developing specialized adaptations to conserve water. Alpine plants have evolved various adaptations to cope with limited water availability. These adaptations may include reduced leaf surface area, deep root systems, and the ability to store water in specialized tissues. The accumulation of secondary metabolites is a common response in plants when they are subjected to drought. Phenolic compounds, including flavonoids and other polyphenols, act as antioxidants. They help protect plants from oxidative stress caused by reactive oxygen species (ROS) produced during drought conditions. Antioxidants neutralize ROS, preventing cellular damage. Prior research has shown the impact of extreme drought on plant diversity in the elevated areas. For example, *Artemisia brevifolia* showed variation in secondary metabolites along with altitudinal gradient in the Ladakh region (low water availability) of the Western Himalayas, which are often known as "cold desert." GCMS analyses showed that the total number of volatile compounds in *A. brevifolia* increased with elevation. HPLC analyses showed no effect of elevation on the total number of phenolic compounds detected in both young and mature leaves. However, the concentration of the majority of phenolic compounds decreased with elevation (Nataraj *et al*., 2022). On the other hand, another study from the same region demonstrated that, metabolome analysis showed decreasing concentration of bioactive phenolics with the increase in altitude in *A. brevifolia* (Hussain *et al*., 2023). The antioxidant activity of the sample extracts from low-altitude sites showed a higher inhibition percentage compared to high-altitude sites. Phenological changes also reported in some plants like *Campanula scheuchzeri* Vil, *Ranunculus montanus* Willd by Cornelius *et al.* (2013), who revealed that, anther dehydration induced by drought stress in alpine and arctic regions. Alpine plants may have these adaptations to enhance water use efficiency, as water availability can be limited in these environments. Reduction in biomass, total leaf count, leaf size and specific leaf area, increase in root biomass observed in *Aciphylla glacialis*, *Oreomyrrhis eriopoda* and *Wahlenbergia ceracea* with increasing elevation (Geange *et al*., 2017).

Wind speed

Wind speed can significantly impact plants in alpine regions, where environmental conditions are often harsh. Wind can exacerbate temperature extremes in alpine regions (Sekar *et al*., 2023). During winter, strong winds can enhance the chilling effect on plants, making them more susceptible to frost damage. In summer, rapid air movement can contribute to cooling, affecting the overall temperature conditions (Crabtree *et al*., 2010). High wind speeds can hinder the process of pollination, which is crucial for the reproduction of many plant species. Wind may disrupt the flight of pollinators and scatter pollen away from its intended destination (Holtmeier *et al*., 2010). In response to the challenging conditions, some alpine plants may adopt a dwarf or prostrate growth form to reduce exposure to wind. This adaptation helps them conserve energy and resist mechanical damage Heydel *et al.* (2014).

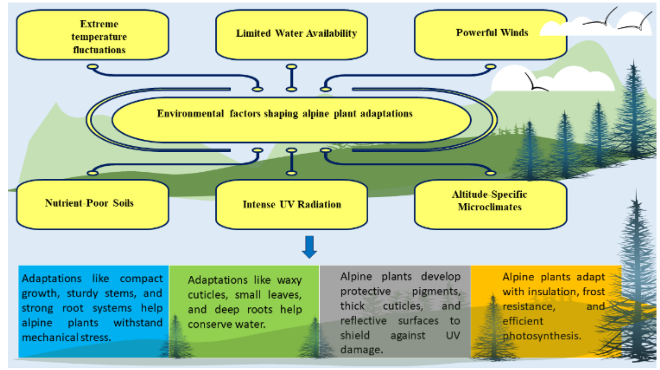

Figure 1. Environmental factors mediated response of alpine and subalpine plant species

Future prospects

Gaining insight into the mechanisms by which alpine plants acclimatize to harsh environments is crucial in formulating effective approaches for their preservation. Given the susceptibility of alpine ecosystems to climate change and human stressors, conservation initiatives can gain valuable knowledge from studying these adaptations. Alpine habitats are distinct and have a vital function in worldwide biodiversity (Sekar *et al*., 2023). Examining plant adaptations offers useful insights into the complex interconnections of plants, microbes, and other creatures in these habitats. Alpine habitats serve as highly responsive markers of climate change. Through the examination of plant adaptations, scientists are able to see the reactions of these ecosystems to changing climatic circumstances, therefore yielding crucial data for climate change studies and forecasts (Cornelius *et al*., 2013). The adaptations exhibited by alpine plants have the potential to serve as a source of inspiration for the advancement of novel technologies and materials. For instance, comprehending the mechanisms by which plants shield themselves from UV radiation might provide valuable insights for developing compounds aimed at sun protection across many sectors. Alpine plants exhibit some adaptations, such as the ability to withstand drought and efficiently use nutrients, which might potentially be beneficial in agricultural practices. The knowledge acquired from these modifications may be utilized to cultivate crops that exhibit greater resilience in the face of demanding environmental circumstances (Jeong *et al*., 2021). Exploring the adaptations of alpine plants offers educational prospects for students and researchers, cultivating a more profound comprehension of plant ecology, evolution, and the interdependence of ecosystems. This understanding enhances the wider domain of biology and environmental science (Nagelmüller *et al*., 2017). Alpine plants frequently generate bioactive chemicals as a component of their adaptations to harsh circumstances. These chemicals have potential uses in the fields of pharmaceuticals and industry, and investigating these modifications can result in the identification of innovative bioactive molecules (Li *et al*., 2022). Alpine ecosystems have a crucial role in providing vital ecosystem services such as water control, carbon sequestration, and habitat for diverse species. Gaining knowledge about the adjustments of alpine plants aids in the evaluation and sustainable management of these functions (Vanhatalo *et al*., 2003).

Table 1. Different factors affecting plants from alpine and subalpine zone and plant response

Plant Name	Factors affecting	Plant response	Reference
Abies faxoniana	Elevated temperature	Promotion of plant growth by increasing net photosynthesis and biomass	Woo *et al*., 2009
Abies faxoniana	Elevated temperature	Promotion of plant growth by increasing net photosynthesis and biomass	Yu *et al*., 2020
Abies koreana	Low temperature	Increase net photosynthesis	Woo *et al*., 2008
Abies spp.	Elevated temperature	Biomass production	Usoltsev *et al*., 2023
Aciphylla glacialis	Water scarcity	Reduction in biomass,total leaf count, leaf size and specific leaf area, increase in root biomass.	Geange *et al*., 2017
Acomastylis elata	Elevated CO_2	Increase in net assimilation rate, growth and productivite	Chandra *et al*., 2023
Aconitum heterophyllum	Elevated CO_2	Increase in total soluble sugar, proline and lipid peroxidation and decrease in starch content, secondary metabolites and leaf nitrogen content	Chandra *et al*., 2023
Aconitum balfourii	Elevated CO_2	Increase in total soluble sugar, proline and lipid peroxidation and decrease in starch content, secondary metabolites and leaf nitrogen content	Chandra *et al*., 2022
Anaphalis nepalensis	Elevated CO_2	Increase in net assimilation rate, growth and productivity	Chandra *et al*., 2024
Androsace tapet	Low temperature and precipitation	Habitat shift	Li *et al*., 2013
Artemisia brevifolia	Drought	Increase in total number of volatile compounds	Nataraj *et al*., 2022
Artemisia brevifolia	Drought	Decreasing concentration of bioactive phenolics	Hussain *et al.*, 2023
Astragalus laxmannii	Elevated temperature	Vegetative and reproductive growth increased significantly	Li *et al.*, 2022
Betula pubescens	Elevated CO_2	Biomass decreased	Vanhatalo *et al*., 2003
Betula spp.	Elevated temperature	Biomass production	Usoltsev *et al*., 2022
Bistorta macrophylla	Elevated CO_2	Decrease in net photosynthesis	Chandra *et al*., 2025
Campanula scheuchzeri Vil	Drought	Anther dehydration	Cornelius *et al.*, 2013
Empetrum hermaphroditum)	Elevated CO_2	No effect	Dawes *et al*., 2011
Kobresia humilis	UV- radiation	Increase in leaf area and fresh weight, early flowering	Shi *et al*., 2022
Kobresia humilis	Elevated temperature	Vegetative and reproductive growth increased significantly	Li *et al*., 2022
Larix decidua	Drought	Reduced plant water availability and transpiration rate	Leo *et al.*, 2014
Larix decidua Mill.	Elevated CO_2	Increase in photosynthesis and stomatal conductance, no change in transpiration rate	Streit *et al*., 2014
Oreomyrrhis eriopoda	Water scarcity	Reduction in biomass, leaf count, leaf size and specific leaf area, increase in root biomass.	Geange *et al.*, 2017
Picea abies	Drought	Reduced plant water availability and transpiration rate	Leo *et al.*, 2014
Picea abies	Elevated CO_2	Biomass decreased	Vanhatalo *et al*., 2003
Picea purpurea	Elevated temperature	Promotion of plant growth by increasing net photosynthesis and biomass	Yu *et al*., 2019
Pinetum typicum	Drought	Reduced plant water availability and transpiration rate	Leo *et al.*, 2014

Pinus mugo	Elevated CO_2	Increase in photosynthesis and stomatal conductance, no change in transpiration rate	Streit *et al*., 2014
Pinus sylvestris	Drought	Reduced plant water availability and transpiration rate	Leo *et al*., 2014
Pinus sylvestris	Elevated CO_2	Biomass production	Vanhatalo *et al*., 2003
Plantago euryphylla	High temperature	Increase in net photosynthesis and respiration rate	Atkin *et al*., 2006
Poa alpina	Low temperature	Inhibition of cell differentiation	Nagelmüller *et al*., 2020
Primula farinosa	High temperature	Reduction in survival rates but increased rosette size and leaf count	Jeong *et al*., 2021
Ranunculus glacialis	Low temperature	Inhibition of root growth	Nagelmüller *et al*., 2019
Ranunculus glacialis	Low temperature	No changes observed in xanthophyll cycle compounds	Streb *et al*., 2003
Ranunculus montanus Willd	Drought	Anther dehydration	Cornelius *et al*., 2013
Rumex alpinus	Low temperature	Changes in root architecture	Nagelmüller *et al*., 2017
Saxifraga hostii	UV- radiation	high absorption in the UV spectrum at higher altitudes	Sedej *et al*., 2020
Soldanella alpina	Low temperature	No change in antioxidant compounds	Streb *et al*., 2003
Stipa purpurea	Elevated temperature	Vegetative growth increased significantly	Streit *et al*., 2014
Trillium govanianum	Elevated CO_2	Decrease in net photosynthesis	Chandra *et al*., 2026
Tussilago farfara	Low temperature	Inhibition of root growth	Nagelmüller *et al*., 2018
Vaccinium gaultherioides	Elevated CO_2	No effect	Dawes *et al*., 2011
Vaccinium myrtillus	Elevated CO_2	Increase in Biomass and leaf nitrogen content	Dawes *et al*., 2011
Wahlenbergia ceracea	Water scarcity	Reduction in biomass, total leaf count, leaf size and specific leaf area, increase in root biomass.	Geange *et al*., 2017

CONCLUSION

The study of alpine plant adaptations is vital for biodiversity conservation, climate change research, and technological innovation. Alpine ecosystems, with their extreme conditions, serve as valuable indicators of climate change impacts. Understanding plant adaptations provides insights into ecosystem resilience and informs conservation strategies. Moreover, these adaptations may inspire bioinspired technologies and materials for various applications. The knowledge gained contributes to agricultural resilience, sustainable tourism, and educational advancements. Alpine plants also offer potential pharmaceutical and industrial applications through the discovery of bioactive compounds. Overall, delving into alpine plant adaptations is not only crucial for preserving these unique ecosystems but also enhances our understanding of plant ecology and evolution, with far-reaching implications for diverse scientific disciplines and practical applications in a rapidly changing world.

CONFLICT OF INTEREST

The author here declares that there is no conflict of interest in the publication of this article.

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