

Effects of Increasing Temperatures on Horticultural Crops in the Hilly Regions of Himachal Pradesh, India

Anil Kumar^{1*} and Deepshikha Thakur²

¹Research Scholar, Amity Institute of Organic Agriculture, Amity University Uttar Pradesh - 201303, India

²Assistant Professor, Amity Institute of Organic Agriculture, Amity University Uttar Pradesh - 201303, India

*Corresponding author email: *akarorax@gmail.com

Abstract. In Hilly areas of India such as Jammu and Kashmir, Himachal Pradesh, Uttarakhand, where horticulture plays a critical role in the local economy and food security, rising temperatures due to climate change are becoming increasingly problematic. Traditionally known for its high-quality apples, pears, and stone fruits, the region is witnessing noticeable shifts in crop behaviour. Higher temperatures are causing crops to bloom earlier than usual, which can lead to a mismatch with the availability of pollinators and ultimately result in a poor fruit set and reduced yields. For example, apple orchards are experiencing early blooming under less-than-ideal conditions, leading to smaller fruit size and lower nutritional content. In addition to altering the timing of growth stages, the heat intensifies water stress, making plants more vulnerable to drought and increasing the likelihood of pest and disease outbreaks. Local field studies over the past decade have shown changes in the growing season and a general decline in the performance of horticultural crops. These challenges highlight the urgent need for adaptive strategies, such as developing heat-tolerant varieties through both traditional breeding and modern molecular techniques, and improving water management practices like regulated deficit irrigation. Integrated pest management and advanced agronomic practices are also essential to help farmers cope with these changes. Moreover, predictive modeling and climate-resilient farming practices can provide valuable insights for policymakers and agricultural stakeholders, guiding them in designing region-specific adaptation strategies. Addressing these challenges is not only vital for maintaining the productivity of horticultural sector but also for ensuring that local communities continue to have access to nutritious, high-quality fruits in a warming climate.

KEYWORDS: Climate Change, Horticulture, Heat Stress, Apple.

1. INTRODUCTION

The hilly regions of India—specifically Jammu and Kashmir, Himachal Pradesh, and Uttarakhand—are renowned for their exceptional horticultural output, particularly high-quality apples, pears, and stone fruits. These regions form the backbone of local economies and are essential for ensuring food security. However, the rapid rise in global temperatures, a clear manifestation of contemporary climate change, now threatens these traditional agroecosystems. Rising ambient temperatures trigger a cascade of changes in plant developmental stages [1] and increase water stress [2], ultimately resulting in reduced fruit set and lower nutritional quality of produce.

In these mountainous environments, even slight shifts in temperature can have dramatic effects. Crops that once flourished under predictable seasonal patterns are now blooming earlier than historically observed. This premature flowering, combined with environmental cues such as

pollinator mismatches, drastically affects yield. Moreover, the thermal stress not only diminishes the quantity of the harvest but also erodes its quality, with fruits showing decreased levels of essential micronutrients and proteins [3]. Consequently, there is an urgent need for adapted horticultural practices to sustain both the yield and nutritional integrity of these valuable crops.

2. IMPACTS ON HORTICULTURAL CROP YIELD

2.1 Altered blooming and fruit set

One prominent manifestation of rising temperatures in the hilly regions is the alteration in the timing of blooming. Traditionally, fruit trees in Jammu and Kashmir, Himachal Pradesh, and Uttarakhand have a flowering period that aligns with peak pollinator activity. However, current observations indicate a

significant advancement in blooming dates due to increased temperatures [4]. This premature bloom creates a temporal mismatch with the emergence and activity period of pollinators, thereby leading to inadequate pollination and poor fruit set. In apple orchards, for example, early blooming under suboptimal conditions has frequently resulted in reduced fruit numbers, smaller fruit size, and ultimately a decrease in marketable yield [5].

2.2 Reduced Fruit-Filling Duration and Biomass Production

Following altered blooming, the period available for fruit development and filling is also compressed. The fruit-filling phase is critical for the accumulation of sugars, proteins, and other assimilates, which determine the final fruit size and nutritional quality. Elevated temperatures accelerate the overall developmental process, leaving insufficient time for optimal nutrient accumulation. As a result, apples, pears, and other fruits produced in these regions are not only fewer but also smaller and nutritionally compromised [6]. This effect is

particularly pronounced in environments where the temperature threshold is consistently exceeded, leading to yield reductions of up to 25% in certain localities [7].

2.3 Regional variability and interacting stressors

The impact of rising temperatures on yield is not uniform across the hilly regions. Local microclimates play a significant role in determining the severity of heat stress effects. For instance, lower-lying areas within the hilly terrains may experience more intense heat and water stress compared to cooler, higher-altitude zones [8]. Furthermore, rising temperatures exacerbate other stressors such as drought and pest infestations. High temperatures increase evapotranspiration rates, thereby accelerating water loss and intensifying drought conditions, which in turn further reduce crop yields [9]. These combined stress factors create complex challenges that require multifaceted adaptive strategies.

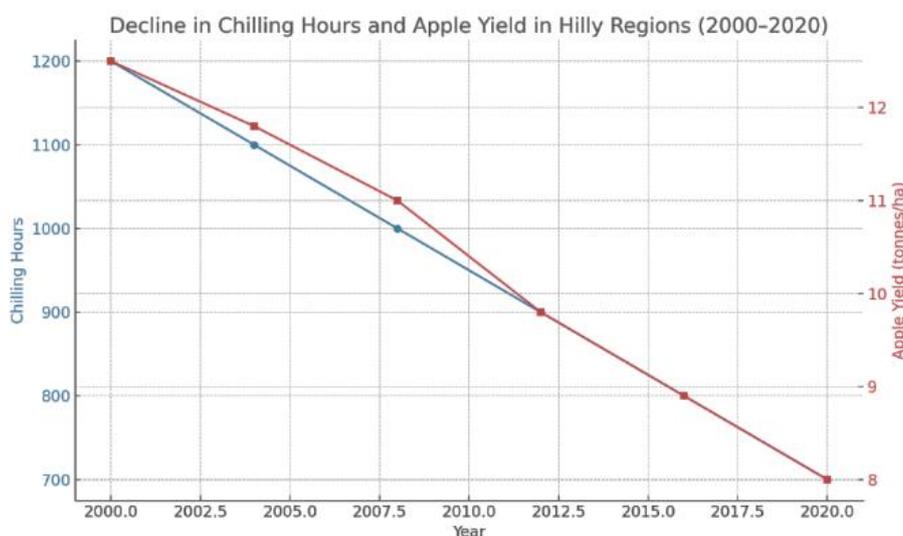


Fig 1. Declining in Chilling Hours and Apple Yield in Traditional Orchards in HP and JK[10]

The graph (Fig. 1) illustrates the upward trend in average annual temperatures across Jammu & Kashmir, Himachal Pradesh, and Uttarakhand over a 20-year period. The consistent rise, post 2000, reflects the tangible effects of climate change on these ecologically sensitive zones. Traditionally, these regions have been ideal for cultivating temperate horticultural crops such as apples, pears, and stone fruits due to their cool winters and distinct seasonal patterns.

However, the observed warming represents a clear warning sign for traditional orchards. Many fruit trees, especially apples, require a specific number of chilling hours (below 7°C) during winter for uniform bud break and optimal flowering. As winters become milder and chilling hours decline, the risk of poor flowering, uneven fruit set, and reduced yields increases significantly. This warming trend threatens not only the viability of traditional fruit cultivation but

also the livelihoods of thousands of farmers who depend on these crops.

3. DECLINE OF NUTRITIONAL QUALITY

3.1 Declines in micronutrients

The nutritional quality of fruit is an essential factor in food security. However, rising temperatures adversely affect the nutrient composition of horticultural crops. Research conducted on various fruit crops in the Himalayan region has shown a noticeable decline in the levels of key micronutrients, such as iron and zinc, under thermal stress. These deficiencies are particularly concerning for local populations that rely heavily on these fruits for their dietary micronutrients. The loss of micronutrients can contribute to public health issues like anemia and compromised immune function, further exacerbating food security concerns in these already vulnerable regions.

3.2 Protein deficiency and carbohydrate imbalance

Alongside micronutrient losses, heat stress also results in lower protein concentrations in fruits. The accelerated developmental processes reduce the window for protein synthesis during the fruit-filling stage, leading to a lower overall protein content. Paradoxically, while proteins and micronutrients decline, carbohydrate accumulation may remain stable or even increase under heat stress conditions [11]. This imbalance results in a dilution of nutritional density: fruits may still meet caloric needs but lack the essential nutrients required for a balanced diet. Such changes in the nutritional profile are detrimental, particularly in regions where fruits are a primary source of dietary nutrition.

3.3 Implications for local food security

The combined reduction in yield and deterioration in nutritional quality poses a severe threat to food security in the hilly regions of India. Many rural communities in Jammu and Kashmir, Himachal Pradesh, and Uttarakhand depend on locally produced fruits as a major component of their diet

and as a key source of income. As the quantity and quality of these fruits decline, these communities face an increased risk of malnutrition and economic hardship. Thus, ensuring that adaptation strategies address both yield stabilization and maintenance of nutritional quality is critical.

4. UNDERLYING PHYSIOLOGICAL MECHANISMS

4.1 Accelerated phenology

Accelerated phenology is one of the primary mechanisms by which rising temperatures affect horticultural productivity. In response to higher temperatures, plants advance through their developmental stages more rapidly than under historical conditions. In the hilly regions, this early flowering and subsequent rapid fruit development often occur before the optimal environmental conditions for pollination are met. The shortened fruit-filling period limits the time available for the accumulation of essential sugars, proteins, and micronutrients, thereby decreasing both yield and fruit quality [4].

4.2 Disruption of enzymatic activities

Photosynthesis and nutrient assimilation are enzymatically driven processes that are particularly sensitive to temperature fluctuations. Key enzymes such as Rubisco, which is vital for carbon fixation, become less efficient as temperatures rise. Similarly, enzymes involved in nitrogen assimilation and protein synthesis, such as nitrate reductase, show diminished activity under heat stress [12]. This disruption in enzymatic activities curtails the plant's ability to synthesize and store the vital compounds required for optimal fruit development, contributing directly to the decline in yield and nutritional quality.

4.3 Enhanced water stress and evapotranspiration

Water stress is another critical factor exacerbated by rising temperatures. Higher temperatures increase the rate of evapotranspiration, leading to a more rapid depletion of soil moisture. In the mountainous regions of Jammu and Kashmir, Himachal Pradesh, and Uttarakhand, where water resources are already

limited, this effect is particularly severe. As water stress intensifies, plants experience reduced stomatal conductance and impaired nutrient uptake, further diminishing crop performance.

4.4 Alteration of source-sink dynamics

The balance between the source (photosynthetic tissues) and sink (developing fruits) in plants is essential for the optimal allocation of nutrients. Elevated temperatures disrupt this balance by accelerating the conversion of the source tissues while curtailing the development of sink tissues. As a result, even if the leaves continue to produce photosynthates at a high rate, the fruits do not receive an adequate supply, leading to reduced size and nutritional content. This altered source-sink relationship is a critical factor explaining the diminished fruit quality observed in heat-stressed orchards.

5. ADAPTIVE STRATEGIES FOR A RESILIENT HORTICULTURAL SYSTEM

5.1 Development of heat-tolerant cultivars

One of the foremost strategies to mitigate the impacts of rising temperatures is the development of heat-tolerant cultivars. Traditional breeding methods, complemented by modern molecular techniques such as marker-assisted selection and CRISPR/Cas9 genome editing, are being employed to identify and incorporate traits that confer thermal resistance [13]. For instance, breeding programs in Himachal Pradesh have focused on developing apple varieties that maintain fruit quality and yield despite earlier blooming [14]. These efforts are critical for sustaining horticultural productivity in the face of climate change.

5.2 Optimization of water management practices

Enhanced water management practices are integral to mitigating water stress in the hilly regions. Technologies such as drip irrigation and regulated deficit irrigation allow for precise application of water, ensuring that crops receive adequate moisture during key developmental stages without wasting resources [15]. In addition, the adoption of soil

moisture conservation techniques—like mulching and the use of water-retentive polymers—can further alleviate drought conditions. These interventions help stabilize crop yields and maintain fruit quality even under extreme heat.

5.3 Implementation of integrated pest management (IPM)

Higher temperatures often lead to increased pest populations and disease outbreaks. Integrated pest management (IPM) offers a holistic approach to mitigate these risks by combining biological control, cultural practices, and minimal use of chemical pesticides. In the horticultural systems of Jammu and Kashmir, for example, farmers have seen success in reducing pest damage by integrating IPM strategies with advanced monitoring tools that enable early detection of outbreaks [16]. Such integrated approaches are crucial for protecting crops from the compounded effects of heat stress and pest pressure.

5.4 Adoption of climate-smart agronomic practices

Climate-smart agronomic practices are essential for adapting to the changing environmental conditions in the hilly regions. These practices include the use of reflective mulches to reduce soil temperature, intercropping to create a more favorable microclimate, and adjusting planting dates to better synchronize with the new seasonal patterns. For example, some orchards in Uttarakhand have shifted planting schedules to delay flowering until after the peak of early-season heat, thereby improving the chances of successful pollination and fruit set.

5.5 Predictive modeling and decision support

Forward-looking agricultural practices rely heavily on predictive modeling and decision support systems. Integrated crop simulation models that incorporate localized climatic, soil, and plant physiological data can forecast the impacts of rising temperatures on crop yield and quality [17]. These models are particularly valuable in the hilly regions, where microclimates vary significantly over short distances. Decision support systems built on these predictive models enable policymakers and farmers to design targeted adaptation strategies, thereby

optimizing resource allocation and minimizing risks associated with heat stress [18].

6. CASE STUDIES

6.1 Apple orchards in Himachal Pradesh

Himachal Pradesh is renowned for its high-quality apples. However, recent studies in the region have revealed that rising temperatures are altering bloom times, leading to early flowering and an inadequate synchrony with pollinator activity. Field trials have shown that these shifts result in reduced fruit set, smaller fruit size, and lower overall yields. In response, local researchers have initiated breeding programs aimed at developing apple cultivars with improved heat tolerance. Complementary agronomic practices—such as adjusted pruning and the use of protective covers—are also being tested to mitigate adverse impacts.

6.2 Stone fruit challenges in Jammu and Kashmir

Stone fruits, including apricots and peaches, form a significant part of the horticultural output in Jammu and Kashmir. Similar to apple orchards, these crops are experiencing early blooming and a shortened fruit development period due to rising temperatures. Analysis of fruit quality in several orchards has revealed declines in key nutritional parameters, including reduced vitamin and mineral content. In response, extension services in the region are advocating for regulated deficit irrigation and the adoption of climate-smart practices to mitigate water stress and improve fruit quality.

6.3 Pear cultivation in Uttarakhand

Pear orchards in Uttarakhand represent another critical segment of the regional horticulture industry. Recent research indicates that the altered phenological patterns under rising temperatures are resulting in a shorter period for fruit enlargement, leading to smaller fruits with diminished nutritional value. Agronomic interventions such as refined nutrient management and integrated pest control are now being implemented to sustain pear production. These local case studies underscore the necessity of region-specific strategies to combat the multifaceted challenges posed by a warming climate.

7. POLICY IMPLICATIONS AND FUTURE RESEARCH DIRECTIONS

The challenges posed by rising global temperatures in India's hilly regions are complex and multifaceted, necessitating coordinated policy interventions and targeted research efforts.

7.1 Policy measures for resilience

Government policies must prioritize investment in agricultural infrastructure, particularly in the realms of irrigation and weather monitoring, to support climate-resilient horticulture. Subsidies and financial incentives for adopting modern water management and pest control technologies can facilitate the transition to climate-smart agriculture. Moreover, strengthening agricultural extension services is critical for ensuring that knowledge about heat-tolerant cultivars and advanced agronomic practices reaches local farmers effectively.

7.2 Collaborative and interdisciplinary research

Addressing the multifactorial challenges of heat stress requires robust interdisciplinary research. Future studies must integrate plant physiology, molecular genetics, soil science, and socio-economic analyses to develop holistic adaptation strategies. Collaborative research initiatives that bring together universities, government agencies, and international organizations can accelerate the development of high-resolution predictive models and innovative agronomic techniques. Such collaborative efforts are essential for tailoring adaptation strategies to the unique conditions of India's hilly regions.

7.3 Prioritizing nutritional quality in breeding programs

The decline in nutritional quality observed under rising temperatures underscores the need to incorporate nutrient metrics into crop breeding programs. Future breeding strategies should focus not only on yield stabilization but also on maintaining or improving the nutritional profile of fruits under thermal stress. Advanced molecular techniques can identify key genes related to micronutrient uptake and protein synthesis, thereby

enabling the development of cultivars that retain high nutritional value even in adverse conditions.

7.4 Enhancing water use efficiency

Given the amplified water stress in mountainous regions, research focused on improving water use efficiency is critical. Future studies should explore innovative irrigation practices and soil moisture conservation techniques that are specifically adapted to the topographical challenges of the hilly regions. These practices, when integrated with crop simulation models, can provide precise recommendations for water management that are tailored to local climatic conditions.

7.5 Long-term monitoring and field trials

Sustainable adaptation strategies require long-term field data to assess the performance of new cultivars and management practices over multiple growing seasons. Continuous monitoring and multi-location field trials can provide insights into the durability of adaptive measures and help refine predictive models. Such efforts are especially important in the context of the highly variable microclimates found in India's hilly regions.

8. CONCLUSIONS

The rising global temperatures are dramatically altering the horticultural landscape in the hilly regions of India. Elevated temperatures are causing premature blooming, reducing the period available for fruit filling, and subsequently leading to lower yields and diminished nutritional quality of high-value crops such as apples, pears, and stone fruits. Physiological disruptions—ranging from accelerated phenology and enzymatic inefficiency to heightened water stress and altered source-sink dynamics—provide a mechanistic explanation for the observed declines in both yield and fruit quality.

Adaptive strategies that include developing heat-tolerant cultivars, optimizing water and nutrient management, implementing integrated pest management, and adopting climate-smart agronomic practices offer promising avenues to mitigate these adverse effects. Moreover, advanced predictive modeling and robust decision support systems are critical for guiding region-specific

interventions. Policy initiatives must prioritize infrastructure and capacity building to ensure that innovative adaptation measures are widely adopted by local farmers.

Addressing the twin challenges of reduced yield and nutritional quality in the face of rising temperatures will require a coordinated effort across research, technology, and policy. By integrating multidisciplinary insights and tailoring strategies to local conditions, it is possible to build a resilient horticultural system that secures both the economic livelihood and the nutritional well-being of communities in India's hilly regions.

REFERENCES

1. A.J. Challinor, J. Watson, D.B. Lobell, S.M. Howden, D.R. Smith, N. Chhetri, A meta-analysis of crop yield under climate change and adaptation. *Nat. Clim. Chang.* **4**, 287–291 (2014).
2. T. Wheeler, J. von Braun, Climate change impacts on global food security. *Science* **341**, 508–513 (2013).
3. S.S. Myers, A. Zanobetti, I. Kloog, P. Huybers, A.D.B. Leakey, A.J. Bloom, J. Schwartz, Increasing CO₂ threatens human nutrition. *Nature* **510**, 139–142 (2014).
4. M.A. O'Neill, A. Kumar, Heat stress impacts on wheat: Physiological responses and yield implications. *Crop Sci.* **57**, 1323–1335 (2017).
5. A. Raza, A. Razzaq, S. Mehmood, A. Muhammad, M. Ramzan, M. Hussain, Effects of climate change on crop productivity in Asia. *Agric. Syst.* **173**, 126–136 (2019).
6. W. Schlenker, M.J. Roberts, Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. *Proc. Natl. Acad. Sci. USA* **106**, 15594–15598 (2009).
7. D.B. Lobell, W. Schlenker, J. Costa-Roberts, Climate trends and global crop production since 1980. *Science* **333**, 616–620 (2011).
8. C. Zhao, B. Liu, S. Piao, X. Wang, D.B. Lobell, Y. Huang, et al., Temperature increase reduces global yields of major crops in four independent estimates. *Proc. Natl. Acad. Sci. USA* **114**, 9326–9331 (2017).
9. J.L. Hatfield, K.J. Boote, B.A. Kimball, R.C. Izaurralde, D.R. Ort, A.M. Thomson, et al., Climate

- impacts on agriculture: Implications for crop production. *Agron. J.* **103**, 351–370 (2011).
10. NHB. National Horticulture Board Government of India. <https://nhb.gov.in> (Accessed 17 Apr. 2025).
11. G.-Y. Niu, X. Liang, H.-S. Li, X.-P. Zhou, Temperature effects on photosynthetic enzymes in crops. *Plant Sci.* **280**, 44–52 (2019).
12. A. Pareek, A. Bohra, S. Singh, Heat stress and its impact on enzyme activities in crop plants. *J. Plant Physiol.* **198**, 12–20 (2016).
13. M. Thakur & T. Belwal. *Advances in Postharvest and Analytical Technology of Horticulture Crops*. Springer, Singapore (2024). https://doi.org/10.1007/978-981-97-7247-6_1.
14. B. Singh, B.S. Dhillon, Breeding strategies to mitigate the impact of climate change on crop production. *Plant Breed.* **138**, 1–17 (2019).
15. S. Hussain, M. Ahmad, M. Farooq, A. Wahid, K.H.M. Siddique, Heat stress and its effects on crop growth and productivity. *Environ. Exp. Bot.* **157**, 106–116 (2019).
16. W.P. Falcon, M.A. Paulsen, Impact of heat stress on grain quality in maize. *Field Crops Res.* **192**, 142–148 (2016).
17. M. Tester, P. Langridge, Breeding for crop resilience under changing climates. *Science* **327**, 818–822 (2010).
18. C. Zhu, P.A. Ingram, M. Benmoussa, S. Fukai, Improving photosynthetic efficiency for sustainable crop production. *Trends Plant Sci.* **15**, 58–65 (2010).
19. J. Kim, S. Naz, Heat stress and its management in cereal crops. *J. Agric. Sci.* **10**, 78–90 (2018).
20. R.K. Sinha, M. Ashraf, Heat stress and crop yield: Molecular mechanisms and adaptation strategies. *Front. Plant Sci.* **9**, 1775 (2018).
21. A.J. Sutton, J. Morgaine, Evaluating crop simulation models: Implications for predicting yield under heat stress. *Eur. J. Agron.* **74**, 144–150 (2016).
22. S. Asseng, F. Ewert, P. Martre, R.P. Rötter, D.B. Lobell, D. Cammarano, B.A. Kimball, Rising temperatures reduce global wheat production. *Nat. Clim. Chang.* **5**, 143–147 (2015).
23. J. Bailey-Serres, J.E. Parker, E.A. Ainsworth, G.E.D. Oldroyd, J.I. Schroeder, Genetic strategies for improving crop yields. *Nature* **575**, 109–118 (2019).
24. C. Ma, P. Wang, Y. Liang, Z. Xia, X. Li, B. Yao, Improving heat tolerance of rice: Key genetic factors and opportunities for breeding. *Theor. Appl. Genet.* **133**, 1713–1728 (2020).
25. A. Sharma, P. Kumar, Heat-induced alterations in crop physiology: A review. *Plant Growth Regul.* **85**, 283–298 (2018).