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Climate change and horticultural crop productivity: Impacts, adaptation, and mitigation strategies

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Abstract

Climate change is emerging as one of the most pressing challenges of the 21st century, with significant implications for horticultural systems worldwide. Fruits, vegetables, ornamentals, spices, and plantation crops are particularly vulnerable to shifting climatic patterns, which can lead to altered phenology, reduced productivity, compromised quality, and heightened susceptibility to pests and diseases. Temperature extremes, erratic rainfall, elevated CO₂ levels, and increased frequency of extreme weather events disrupt normal growth cycles and physiological processes, threatening both yield and nutritional quality. This review synthesizes current knowledge on the impacts of climate change on horticultural crop production, emphasizing both biotic and abiotic stressors. It provides an in-depth analysis of adaptation strategies, including the development of climate-resilient cultivars, optimized irrigation and nutrient management, use of protective structures, and integrated pest and disease management practices. The review also discusses mitigation approaches that reduce greenhouse gas emissions and improve resource-use efficiency within horticultural systems. Furthermore, the paper highlights emerging research areas, such as the integration of precision agriculture, remote sensing, and modeling tools to predict crop performance under future climate scenarios. Policy interventions, capacity-building initiatives, and collaborative frameworks are identified as essential for implementing effective adaptation and mitigation strategies. By consolidating scientific evidence and practical approaches, this review underscores the urgent need for proactive measures to sustain global horticultural productivity and ensure food security. Ultimately, addressing climate change impacts through informed strategies will help build resilient horticultural systems capable of meeting the nutritional and economic demands of a growing global population.

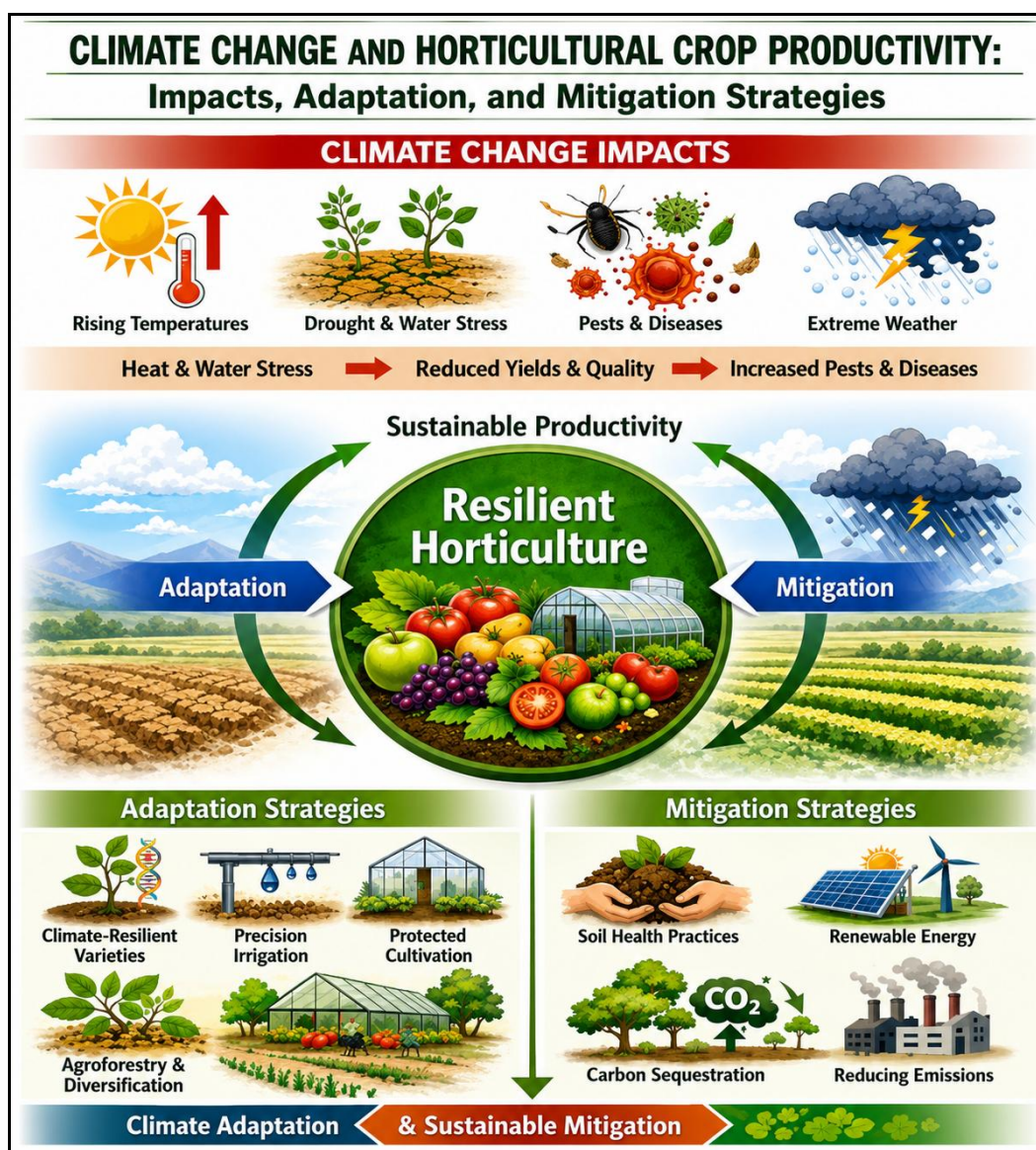
Keywords: Climate change, horticultural crops, adaptation, mitigation, resilience, fruit and vegetable production

Introduction

Climate change refers to long-term alterations in temperature, precipitation patterns, and overall climate variability driven by both natural processes and increasing anthropogenic greenhouse gas (GHG) emissions, such as carbon dioxide and methane, from fossil fuel combustion, deforestation, and industrial activities. These sustained changes are disrupting ecosystem functions across the globe, with agriculture being one of the most climate-sensitive sectors. Rising global temperatures and more frequent extreme weather events — including heatwaves, droughts, floods, and erratic rainfall — directly affect plant physiological processes and crop productivity (Muchie and Assefa, 2021; Wang *et al.*, 2025) ^[2, 4]. Horticultural crops, especially fruits and vegetables, are particularly vulnerable because of their specific requirements for flowering, pollination, fruit set, and quality development, all of which depend on stable temperature and moisture conditions (Pati *et al.*, 2025) ^[5]. Even slight deviations in climatic cues can alter phenology and growth stages in perennial and high-value horticultural crops, leading to reduced yields and compromised fruit quality (Malhotra, 2017) ^[1]. Elevated temperatures can accelerate respiration and disrupt reproductive success, while irregular precipitation patterns can cause water stress or waterlogging, further impairing growth and development. Additionally, these climatic shifts exacerbate pest and disease pressures, creating additional stress for sensitive

horticultural plants. Because fruit crops have narrow climatic thresholds for optimal performance, climate variability and extremes pose serious challenges to sustaining productivity,

quality, and economic viability within horticultural systems under future climate scenarios (Bibi and Rahman, 2023) ^[3].



2. Climate Change Impacts on Horticultural Crop Productivity

2.1. Temperature Stress and Phenology

Elevated temperatures strongly affect plant physiological processes, including photosynthesis, respiration, and reproductive development. Heat can denature key enzymes, reduce carbon fixation, and accelerate respiration, lowering the energy available for growth and yield (Mahajan *et al.*, 2025) ^[6]. Reproductive stages are particularly sensitive, with high temperatures impairing pollen viability, fertilization, and causing flower drop, directly reducing fruit numbers (Kumar *et al.*, 2025) ^[7]. In tomato, apples, and grapes, heat stress can reduce fruit set, accelerate phenology, shorten growing seasons, and diminish overall yield and quality (Castanares, 2025; Muchie and Assefa, 2021) ^[8, 21]. High temperatures also trigger fruit cracking, poor coloration, and quality deterioration, while inducing oxidative stress and membrane instability (Do *et al.*, 2024; Kumar *et al.*, 2025) ^[9, 7]. Overall, even moderate temperature increases can shorten developmental phases, lower crop yields, and compromise fruit quality in sensitive horticultural species (Mahajan *et al.*, 2025) ^[6].

2.2. Water Stress: Drought and Irrigation Challenges

Climate change is altering rainfall patterns and increasing the frequency, severity, and duration of droughts, particularly in arid and semi-arid regions, reducing soil moisture and imposing water stress on plants. Under drought, stomatal closure conserves water but limits CO₂ uptake, reducing photosynthetic efficiency and growth (Huang and Jin, 2025) ^[11]. Reduced stomatal conductance slows carbon assimilation and metabolic activity, diminishing biomass and yield in many horticultural crops (Fahad *et al.*, 2017) ^[13]. Water stress also disrupts leaf turgor and expansion, impairing overall plant vigor, while physiological and biochemical changes can reduce chlorophyll content and enzyme activity. Nutrient uptake is restricted due to limited root growth and reduced mass flow, lowering both yield and nutrient quality, with fruits and vegetables showing smaller size, lower sugar content, and compromised nutritional profiles (Naik *et al.*, 2017) ^[14]. Drought further increases oxidative stress and alters hormonal balances, negatively affecting growth and performance (Lei *et al.*, 2025) ^[12]. Overall, altered precipitation and increased drought frequency under climate change threaten stomatal function, photosynthesis, nutrient uptake, and the

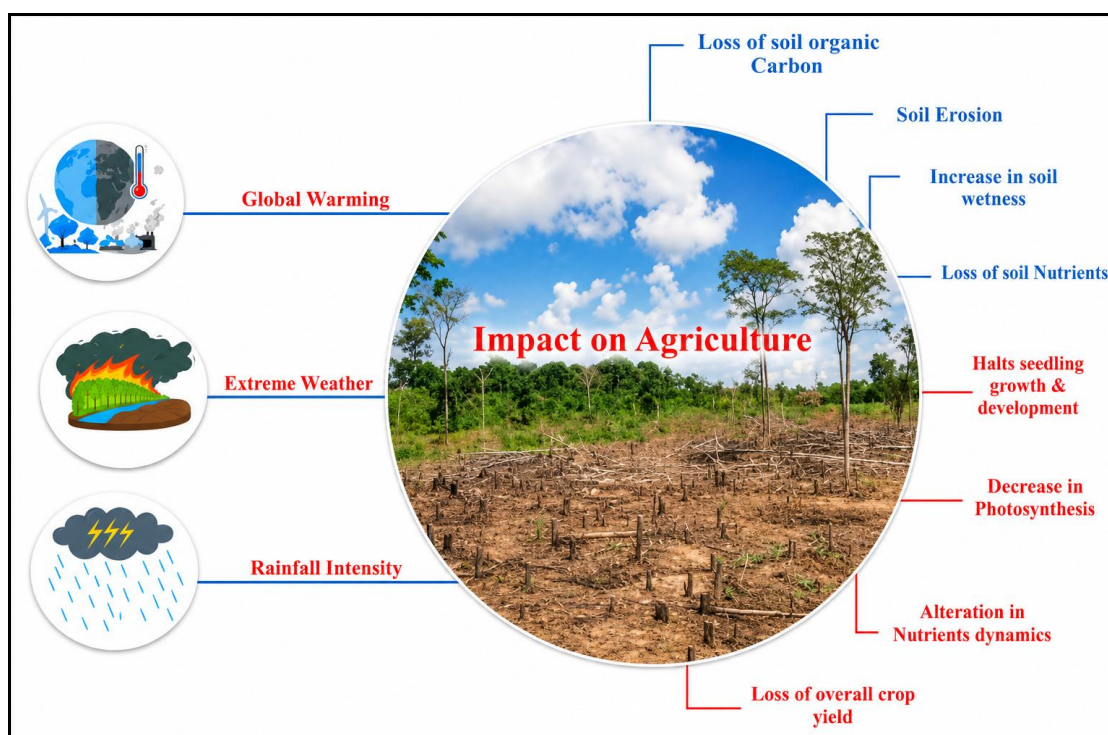
productivity and quality of horticultural crops (Cushman *et al.*, 2022) ^[10].

2.3. Elevated CO₂ and Crop Responses

Elevated atmospheric CO₂ can enhance photosynthesis and biomass by increasing carbon fixation and reducing stomatal conductance, particularly in C₃ crops under non-stress conditions (Dong *et al.*, 2019) ^[18]. FACE experiments and meta-analyses report yield increases of ~18% in some C₃ species (Vanaja *et al.*, 2024) ^[19]. In crops like tomato and strawberry, elevated CO₂ can also improve fruit yield, sugar content, and vitamin C levels (Doddrell *et al.*, 2023) ^[16]. However, these benefits are often offset by concurrent stresses. Higher temperatures accelerate photorespiration, reduce enzyme efficiency, and shorten developmental phases. Reduced stomatal conductance can limit transpiration cooling under heat stress. Nutrient limitations, especially nitrogen, further constrain growth and yield responses (Dong *et al.*, 2018) ^[17]. Meta-analyses indicate that while soluble sugars and antioxidants often increase, some nutrients such as protein, magnesium, iron, and zinc may decline. Combined heat, water, and nutrient stresses under climate change can therefore negate the “CO₂ fertilization effect,” limiting productivity gains under real-world conditions (Rangaswamy *et al.*, 2021; Malhi *et al.*, 2021; Dusenget *et al.*, 2019) ^[15, 21, 20].

2.4. Pest and Disease Pressure

Warming climates are expanding the geographic range of many pests and their disease vectors, allowing them to invade regions previously too cold and increasing the severity of infestations in horticultural systems. Rising temperatures often speed up pest development and reproduction, resulting in more generations per season and higher population pressures on vegetable and fruit crops. Studies report that warmer conditions can accelerate insect life cycles such as those of aphids and mite pests, increasing their abundance and crop damage (Ravuri *et al.*, 2025) ^[24]. Climate change is also linked to greater spread and incidence of plant diseases through enhanced vector activity and extended pathogen survival. Additionally, higher temperatures and water stress can weaken plant immune responses and disrupt natural plant defences, making crops more susceptible to pest attack and disease (Teodoro-Paulo *et al.*, 2025; Ghini *et al.*, 2011) ^[26, 23]. These climatic shifts also reduce the effectiveness of traditional pest management strategies, including biological control agents and some pesticides, as pests adapt and overwinter more successfully under milder conditions (Ma *et al.*, 2021) ^[25]. Collectively, these changes intensify pest and disease pressures on horticultural systems, challenging sustainable crop protection (Haokip *et al.*, 2020) ^[22].



Source: Bibi and Rahman (2023) ^[3]

2.5. Quality and Nutritional Effects

Climate factors such as heat and water deficit not only reduce yield but also degrade fruit quality and nutritional density. Elevated temperatures and drought stress can alter sugar accumulation and pigment synthesis, leading to changes in flavour and reduced soluble sugar content under water deficit despite some varietal variation (Jiang *et al.*, 2020) ^[31]. High temperatures have been shown to soften fruit texture and reduce firmness in raspberry, suggesting shorter shelf life and quality loss under future warming scenarios (Aguilar *et al.*, 2025) ^[30]. Heat and erratic moisture availability also increase physiological disorders such as fruit cracking and surface defects in apples,

which are more frequent under high temperature and limited irrigation (Do *et al.*, 2024) ^[9]. Water stress and deficit irrigation influence the internal balance of soluble solids, potentially increasing sugar concentration but also elevating cracking risk through osmotic imbalance and high turgor pressure (Wu *et al.*, 2025) ^[28]. Severe and prolonged drought generally lowers fruit size and can disrupt nutrient uptake, limiting accumulation of essential vitamins and minerals (Jyoti *et al.*, 2025) ^[27]. Overall, heat and water stress under changing climate conditions compromise not just yield but sensory quality, texture, and nutritional attributes of fruits, challenging both production and marketability (Manzoor *et al.*, 2024) ^[32].

Table 1: Climate Change Stressors and Their Impacts on Major Horticultural Crops

Climate Stressor	Physiological & Phenological Effects	Yield & Quality Impacts	Highly Affected Horticultural Crops
Rising Mean Temperature	Accelerated phenology, increased respiration, pollen sterility, reduced fruit set	Yield decline, smaller fruit size, sunburn, poor coloration	Apple, grape, tomato, citrus, strawberry
Heat Waves	Protein denaturation, membrane instability, oxidative stress	Flower drop, fruit cracking, reduced shelf life	Mango, tomato, capsicum, banana
Altered Rainfall Patterns	Water stress or waterlogging, nutrient imbalance	Reduced yield stability, poor root health	Onion, citrus, papaya, litchi
Prolonged Drought	Reduced photosynthesis, stomatal closure	Lower fruit weight, poor juice content	Grape, pomegranate, ber
Elevated CO ₂	Increased photosynthesis but nutrient dilution	Variable yield response, reduced mineral density	Tomato, cucumber, leafy vegetables
Increased Pest & Disease Pressure	Faster pest life cycles, expanded geographic ranges	Higher crop losses, increased pesticide use	All horticultural crops (notably vegetables)
Extreme Weather Events (hail, frost, cyclones)	Physical damage, disrupted flowering cycles	Complete crop failure in severe cases	Apple, peach, banana, citrus

3. Adaptation Strategies for Horticulture

3.1. Climate-Smart Crop Management

Climate-smart practices include:

- Precision irrigation such as drip and micro-sprinkler systems to improve water use efficiency (Ferreira *et al.*, 2024; St Fort *et al.*, 2025) ^[34, 37].
- Protected cultivation technologies like shade nets and evaporative cooling to moderate microclimates (Nguyen *et al.*, 2022; Rabbi *et al.*, 2019) ^[36, 35].
- Soil and water conservation measures to enhance resilience to variability (Ali, 2024; Kabato *et al.*, 2025) ^[38, 33].

These practices help maintain productivity while reducing vulnerability to climate extremes.

3.2. Crop Diversification and Agroforestry

Diversification and integration of agroforestry systems boosts ecological stability, improves microclimates, and can enhance carbon sequestration — contributing both adaptation and mitigation benefits (Bhandari *et al.*, 2025; Colmenares *et al.*, 2020) ^[39, 40].

3.3. Breeding for Climate Resilience

Traditional and modern breeding approaches are being used to develop cultivars tolerant to heat, drought, salinity, and flood stresses. Marker-assisted selection and genomic tools accelerate the development of climate-resilient varieties (Raya *et al.*, 2025; Tyagi *et al.*, 2024) ^[42, 41].

3.4. Decision Support and ICT Tools

Information and Communication Technology (ICT) tools, weather-based advisories, and decision support systems help farmers anticipate adverse conditions and adjust planting, irrigation, and harvesting schedules accordingly (Ramaraj *et al.*,

2023; Chetri *et al.*, 2024) ^[44, 43].

3.5. Protected Cultivation and Technical Innovations

Climate-controlled environments such as greenhouses and high tunnels help buffer adverse climatic effects, especially for high-value vegetables like tomato, cucumber, and peppers, facilitating year-round production with enhanced stability (Dongre *et al.*, 2025; Gude *et al.*, 2022) ^[45, 46].

4. Mitigation Strategies

4.1. Carbon Sequestration and Soil Management

Horticultural soils can act as carbon sinks. Practices such as cover cropping, organic amendments, and reduced tillage improve soil carbon storage and reduce net GHG emissions (Jayara *et al.*, 2023; Delate *et al.*, 2010) ^[47, 48].

4.2. Energy-Efficient Infrastructure

Use of renewable energy (solar, wind) for water pumping, cooling, and greenhouse operations can lower carbon footprints while enhancing sustainability (Acosta-Silva *et al.*, 2019; Espitia *et al.*, 2024) ^[49, 50].

4.3. Landscape-Level Planning

Integrating trees, hedgerows, and diversified perennial plantings in horticultural landscapes increases carbon storage and provides microclimatic buffering for crops (Kumara *et al.*, 2023; Rathore *et al.*, 2022) ^[51, 53].

4.4. Policy and Incentives

Policymaking that supports climate-friendly practices — through subsidies for climate-smart technologies, crop insurance, and research funding — encourages rapid adoption of mitigation strategies across horticulture.

Table 2: Integrated Adaptation and Mitigation Strategies for Climate-Resilient Horticulture

Strategy Category	Key Interventions	Adaptation Benefits	Mitigation Benefits	Representative Examples
Climate-Resilient Breeding	Heat, drought, salinity-tolerant cultivars; rootstocks	Stable yields under stress	Reduced input dependency	Heat-tolerant tomato hybrids, drought-tolerant mango rootstocks
Precision Water Management	Drip irrigation, sensor-based irrigation scheduling	Improved water-use efficiency	Lower energy use & emissions	Micro-irrigation in grape and citrus
Protected Cultivation	Shade nets, greenhouses, evaporative cooling	Microclimate regulation	Efficient resource use	Tomato and capsicum under polyhouses
Soil Health Management	Organic amendments, mulching, cover crops	Improved moisture retention	Carbon sequestration	Compost-based orchard systems
Agroforestry & Diversification	Tree-crop integration, mixed cropping	Microclimate buffering	Long-term carbon storage	Fruit-tree-based agroforestry
Digital & AI-Based Tools	Climate forecasting, DSS, remote sensing	Early stress detection	Reduced wastage & inputs	Weather-based advisories
Renewable Energy Use	Solar pumps, energy-efficient cold storage	Cost reduction	Reduced GHG emissions	Solar cold rooms for fruits

5. Socio-Economic Dimensions

Smallholders and horticultural producers in developing regions are often the most vulnerable due to limited access to technology, credit, and adaptation resources. Strengthening extension services, climate finance, and equitable policy frameworks are essential to enable adaptive capacity (Berhanu *et al.*, 2024; Ojo *et al.*, 2024) ^[54, 52].

6. Case Studies and Examples

6.1. Mediterranean Greenhouse Horticulture

In Mediterranean regions, greenhouses face rising temperatures and higher vapor pressure deficits (VPD), increasing water and energy needs. Adaptive strategies include precision irrigation, structural retrofitting, and renewable energy integration (Fanourakis *et al.*, 2025) ^[55].

6.2. Crop Adaptation in India

Extension and weather forecasting tools in states like Telangana have helped farmers plan operations around changing monsoon patterns, improving yields and resilience (Harshini *et al.*, 2023) ^[56].

7. Future Research Directions

Critical areas for future research include:

- Crop-specific climate response studies across agro-ecological zones.
- Genomic and phenomic tools for accelerating resilient crop development.
- Integration of remote sensing and machine learning for climate risk modeling.
- Value chain analyses to reduce climate-induced post-harvest losses.

8. Conclusion

Climate change poses a growing threat to horticultural productivity through rising temperatures, erratic rainfall, drought, and increasing pest and disease pressures, which directly affect crop growth, yield stability, and quality. Horticultural crops are especially vulnerable due to their sensitivity during critical stages such as flowering, fruit set, and maturation. Heat stress disrupts physiological processes, water scarcity limits photosynthesis and nutrient uptake, and shifting pest dynamics intensify production risks. However, these challenges can be addressed through an integrated framework combining adaptation strategies, mitigation measures, and technological innovations. Climate-resilient cultivars, efficient water management, protected cultivation, soil carbon sequestration, renewable energy use, and precision agriculture tools can significantly enhance resilience. Strong policy support through incentives, climate finance, extension services, and research investment is equally vital. Collective global action and climate-aware planning are essential to sustain horticultural productivity, farmer livelihoods, and nutritional security under future climate change.

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