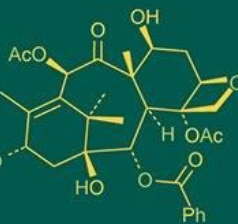
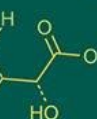


International Journal of Advanced Biochemistry Research



ISSN Print: 2617-4693
ISSN Online: 2617-4707
NAAS Rating (2026): 5.29
IJABR 2026; SP-10(2): 764-769
www.biochemjournal.com
Received: 12-12-2025
Accepted: 16-01-2026

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Climate-induced challenges in fruit crop production and adaptive management strategies: A review

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DOI: <https://www.doi.org/10.33545/26174693.2026.v10.i2Sj.7714>

Abstract

Climate change and agriculture are closely interlinked, with changing climatic conditions emerging as a significant source of abiotic and biotic stresses that threaten sustainable fruit production. According to the Intergovernmental Panel on Climate Change and the United Nations Framework Convention on Climate Change, rising global temperatures, altered precipitation patterns, and increasing greenhouse gas concentrations are accelerating environmental variability, particularly in vulnerable regions such as the Indian subcontinent. Climate plays a decisive role in determining the distribution, phenology, productivity, and quality of perennial fruit crops, as well as the incidence of pests and diseases. Variations in temperature and rainfall directly influence physiological processes including photosynthesis, respiration, flowering, pollination and fruit development. Warmer winters reduce chilling accumulation in temperate fruits, resulting in irregular bud break and poor fruit set, while heat stress in tropical fruits accelerates phenological stages and shortens effective reproductive periods. Climate change also alters area suitability for several fruit crops by shifting agro-climatic zones, thereby affecting regional production systems. In addition, increased frequency of extreme weather events intensifies pest and disease pressure and disrupts plant-pollinator interactions, leading to unstable yields and reduced fruit quality. Although elevated atmospheric CO₂ may enhance photosynthesis and water-use efficiency under certain conditions, these benefits are often offset by heat and moisture stress. Sustainable fruit production under changing climates therefore requires integrated adaptation and mitigation strategies, including conservation of genetic resources, development of climate-resilient cultivars and rootstocks, improved orchard microclimate management and soil carbon enhancement. Understanding the complex interactions between climate variables and fruit crop physiology is essential for ensuring long-term productivity and food security.

Keywords: Climate change, agriculture, production, quality and resilient

Introduction

Climate change refers to a long-term alteration in the Earth's climate system, characterized by persistent changes in temperature, precipitation and other atmospheric conditions over extended periods. A change that is attributed directly or indirectly to human activity which alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods" is how the UNFCCC defines climate change. These changes arise from complex interactions among the biosphere, hydrosphere, cryosphere, and atmosphere (Bhattacharjee *et al.*, 2022) [5]. While natural processes such as volcanic eruptions and continental drift have historically influenced the climate, recent decades have witnessed an accelerated rate of change primarily driven by human activities. According to IPCC, In 2025, climate data indicated it was among the top three warmest years on record, with temperatures 1.33 °C to 1.53 °C above pre-industrial levels. Oceans absorbed over 90% of excess heat, while sea levels continued to rise. IPCC also depicted, the average temperature in the Indian subcontinent would rise by 0.5 to 1.2 °C by 2020, 0.88 to 3.16 °C by 2050 and 1.56 to 5.44 °C by 2080, depending on future progress.

Anthropogenic emissions, particularly greenhouse gases (GHGs), have substantially modified the composition of the atmosphere. The accumulation of gases such as carbon dioxide (CO₂) enhances the atmosphere's ability to trap outgoing infrared radiation, resulting in warming of the surface-troposphere system. Atmospheric CO₂ concentrations have increased dramatically since the industrial era, exceeding 423 ppm in the mid-2024s and continuing to rise thereafter.

This escalation in greenhouse gas levels has been accompanied by a measurable increase in global average temperatures.

Historical records indicate that global air temperatures rose significantly during the 20th century and continue to show an upward trend. Climate projections suggest that by the end of the 21st century, average global temperatures may increase by several degrees Celsius. Such warming is expected to intensify climate variability, leading to irregular rainfall patterns and a higher frequency of extreme weather events, including droughts, floods, and heat waves. Regional assessments further indicate that areas such as the Indian subcontinent are particularly vulnerable to rising temperatures and climatic instability.

Climatic factors constitute one of the most decisive environmental determinants of fruit crop productivity, as they regulate a wide range of physiological, morphological, and biochemical processes throughout the plant life cycle (Jangra, 2013) ^[16]. Variability in temperature, rainfall, humidity, and radiation directly influences vegetative growth by modifying plant vigour, canopy architecture, leaf area development, and photosynthetic efficiency. These vegetative alterations subsequently affect reproductive performance, including floral initiation, pollination success, fruit set, and sink strength. Under suboptimal or fluctuating climatic conditions, fruit crops often exhibit reduced reproductive efficiency, leading to lower yields and compromised fruit development (Ameglio, 2004).

Climate-induced stress also has profound consequences for fruit quality attributes. Elevated temperatures and irregular moisture regimes interfere with pigment biosynthesis, carbohydrate accumulation, and cellular expansion, resulting in smaller fruits with poor colour development, reduced juice content, and altered texture. Such changes negatively affect organoleptic properties and market acceptability. In addition, accelerated metabolic activity under heat stress shortens post-harvest life by increasing respiration and ethylene production, thereby reducing storage potential and shelf stability. Climatic stress further predisposes plants to biotic pressures by weakening defence mechanisms, which can increase susceptibility to insect pests and pathogenic organisms (Jangra, 2013) ^[16].

Temperate fruit crops are particularly vulnerable because their growth cycles are tightly synchronized with seasonal climatic cues, especially chilling and heat accumulation requirements. Sudden or unseasonal weather fluctuations during sensitive phenological stages—such as dormancy release, flowering, and early fruit development—can disrupt physiological homeostasis. These disruptions impair the adaptive capacity of temperate species in regions where they have historically been well established (Osorio-Marín *et al.*, 2024) ^[23]. As climate variability intensifies, the mismatch between crop requirements and prevailing environmental conditions is expected to escalate, posing substantial risks to yield stability and long-term sustainability of temperate fruit production systems (Bhattacharjee *et al.*, 2022) ^[15].

Projected alterations in temperature and rainfall patterns are expected to substantially transform tropical and temperate fruit production systems by influencing orchard location, water availability, and crop performance. Increased irrigation demand, reduced water-use efficiency, and heightened pressure from pests, diseases, and physiological disorders such as sunburn and fruit cracking are emerging concerns, while in temperate regions insufficient winter

chilling and rising minimum temperatures disrupt dormancy and stable fruiting (Das *et al.*, 2025) ^[9]. Because perennial fruit crops rely on narrowly defined climatic thresholds for sustained productivity, these evolving environmental constraints highlight the urgent need to understand climate-crop interactions in depth. This context provides the foundation for examining the specific effects of climate change on fruit crops and the development of effective mitigation and adaptation strategies, which are discussed in the following sections.

Climate-Induced Challenges in Fruit Crop Production

Climate Change effect on Phenology of Fruit Crops

Climate change is causing noticeable shifts in plant phenology, particularly in the timing of vegetative and reproductive growth in fruit trees. Flowering is a crucial stage because it determines fruit set, yield, and overall productivity. Warmer winters have reduced the accumulation of chilling hours required for proper dormancy release in temperate fruit crops such as Apple and pear. When chilling requirements are not adequately met, flower primordia may partially or completely abscise during mild winters, producing weak bud clusters that resemble leafy spurs. This disruption leads to delayed and uneven flowering, affecting the normal progression of reproductive development (Luedeling *et al.*, 2023) ^[23].

Insufficient chilling further results in incomplete blossom formation, poor pollen viability, and weak ovule development, which collectively reduce fruit set and yield. Both the qualitative and quantitative aspects of flowering and fruiting are strongly dependent on adequate chilling exposure. An increase in the average growing temperature of 2-3 °C accelerated flowering, veraison, and harvest by 13-19 days in grape (Gaiotti, 2009) ^[10]. As a result, climate change has led to irregular flowering patterns, inconsistent fruiting, and fluctuations in productivity. These phenological disturbances highlight the need for adaptive orchard management practices, including the development of low-chill cultivars and improved cultural strategies, to sustain fruit production under changing climatic conditions.

Climate Change effect on physiology of Fruit Crops

In Indian climatic conditions, increased atmospheric CO₂ concentration strongly influences the physiological state of crops by enhancing photosynthesis and biomass production in major crops such as rice, wheat, grapevine, mango, and citrus (Maity *et al.*, 2022) ^[20]. Elevated CO₂ generally increases net photosynthetic rate while reducing stomatal conductance, thereby improving water-use efficiency, which is beneficial in many semi-arid regions of India (Parmar *et al.*, 2024) ^[24]. For example, studies on Indian grape cultivation, similar to observations in regions like Portugal, show improved growth and yield under higher CO₂ (Ainsworth & Long, 2023) ^[2], and perennial fruit crops such as citrus exhibit increased root, leaf, and branch biomass under CO₂ enrichment (Maity *et al.*, 2022) ^[20].

However, these benefits are often moderated by rising temperatures and irregular monsoon rainfall patterns linked to climate change in India, as increased heat and soil water evaporation can counteract CO₂ fertilization effects, leading to shorter crop growth periods, yield instability, and greater variability in agricultural production (Parmar *et al.*, 2024; Ainsworth & Long, 2023) ^[24, 2].

Heat stress intensifies evapotranspiration in plants, causing stomatal closure that restricts CO₂ entry, increases respiratory losses, and ultimately suppresses photosynthesis (Hasanuzzaman *et al.*, 2020) ^[14]. Climate projections indicate a substantial decline in winter chilling accumulation in many horticultural regions, which has critical implications for temperate fruit crops (Luedeling *et al.*, 2023) ^[23]. In peach cultivars, warmer winters disrupt normal phenological cycles, leading to irregular and delayed flowering, extended bloom periods, flower abortion, and consequent yield reduction, as chilling requirements are closely linked to reproductive success in stone fruits (Campoy *et al.*, 2011) ^[7]. Elevated temperatures also interfere with pollination processes, a key determinant of global food production (García-Mozo, 2022) ^[11], and can benefit crops in regions that traditionally experience excessively harsh winters.

Climate change further disturbs plant-pollinator relationships through both phenological shifts and geographical redistribution, where pollinators such as *Apis mellifera* may become active earlier than the flowering peaks of their forage plants (Kudo & Cooper, 2019) ^[17]. Crops that rely on cross-pollination or specialized pollinators are particularly vulnerable to these mismatches (Scaven and Rafferty, 2013) ^[29]. In tropical fruit crops, rising temperatures accelerate developmental processes; for example, in mango, rapid panicle growth shortens the effective pollination window, and warm night conditions may convert floral buds into vegetative shoots (Singh *et al.*, 2020) ^[31]. Fruit trees are especially sensitive to climatic variability because of their extended flowering duration and hormone-regulated growth cycles (Sugiura and Honjo, 2021) ^[33]. Crops such as mango and litchi already exhibit shifts toward earlier or irregular flowering and harvest under changing climates (Rajpurohit *et al.*, 2022) ^[27]. Specific environmental conditions—such as low temperature, high humidity, and cloudy weather—can delay panicle emergence and reduce the proportion of hermaphrodite flowers, further constraining productivity, while climatic stress is also associated with increased incidence of physiological disorders like mango malformation (Kumar *et al.*, 2017) ^[18].

Climate Change effect on Area Suitability of Fruit Crops

Year-to-year fluctuations in flowering, productivity, and fruit quality of tropical crops are closely linked to irregular rainfall patterns (Bhattacharjee *et al.*, 2022) ^[5]. Changes in precipitation distribution influence soil moisture availability and plant physiological processes, which in turn affect flowering intensity and fruit development. In recent decades, global warming has contributed to an gradual expansion of tropical climatic zones, creating opportunities for the cultivation of tropical fruits in newly suitable regions. Even a modest temperature increase of about 1 °C can significantly shift the geographic suitability of fruit-growing areas, rendering some traditionally productive regions only marginally suitable while opening up new zones for cultivation. These temperature changes are expected to strongly influence the reproductive biology of tropical fruit crops (Bhattacharjee *et al.*, 2022) ^[5].

Rising temperatures exert two major stresses on crop performance: restriction of vegetative growth and reduction in fruit set. Excess heat, combined with increased transpiration demand, is particularly harmful to fruit crops

that are sensitive to water loss. For mango varieties such as Dashehari and Alphonso, a temperature increase of 0.7-1.0 °C may substantially alter the region's best suited for high-quality production. The optimal area for Dashehari cultivation is projected to shrink considerably with further warming, while Alphonso production may become increasingly confined to climatically favourable coastal belts such as Ratnagiri, where local conditions may buffer temperature stress (Calberto *et al.*, 2015) ^[6].

Climate change projections for banana production indicate a complex pattern of shifting suitability. Warmer conditions may expand banana-growing regions, particularly in areas where the average temperature reaches or exceeds 24 °C. However, long-term temperature analyses across multiple global sites reveal a consistent warming trend that raises concerns about extreme heat stress. Certain locations, including Rajasthan, parts of Uttar Pradesh, and regions of Maharashtra, are projected to experience excessively high temperatures that could suppress banana growth and productivity. Overall, while tropical climates may extend into new territories, existing tropical zones are likely to face increasing risks from temperature extremes.

Climate Change effect on Pest and Disease Incidence in Fruit Crop

Climate change is reshaping pest and disease dynamics in fruit crops by modifying temperature patterns, rainfall distribution and flowering behavior. These environmental shifts can encourage the emergence of new pests, convert previously minor pests into major threats, and weaken existing host resistance. Reports from the National Research Centre for Banana indicate that Sigatoka disease has recently reached destructive levels in Maharashtra, a region where it was once of little concern, highlighting how changing climate conditions can alter regional disease profiles. Increased frequency of heavy and stormy rainfall also favours bacterial gummosis in pome and stone fruits. More broadly, climate change influences pathogen life cycles, infection rates, and host-pathogen interactions, thereby reshaping the epidemiology of many fruit diseases (Ahmad *et al.*, 2011) ^[1].

Temperature rise has complex effects on insect populations and vector dynamics. Seasonal variations in heat and rainfall directly influence insect development, survival, and reproduction, leading to shifts in geographic distribution, faster population growth, and altered synchronization between pests and crop phenology. In tropical environments, warming may exceed the physiological optimum of some insect species, potentially reducing certain vector populations and thereby lowering the incidence of specific viral diseases (Coakley *et al.*, 1999) ^[8]. However, higher temperatures can accelerate the development of other pests; for example, fruit fly activity intensifies under warmer conditions in mango-growing regions. Similarly, projected climate scenarios suggest changes in the life cycle timing of key pests in apple orchards, increasing the difficulty of timely pest management.

Future warming is also expected to increase the frequency of additional pest generations in some regions, raising the need for more intensive protection measures. In India, climate projections indicate a higher likelihood of an extra generation of some pests which would require extended pest control programs and may elevate the risk of pesticide residues on fruits (Parmesan *et al.* At the same time, growers

are already experiencing rising management costs. In citrus orchards of Punjab, increased disease pressure, insect infestations, and water demand associated with climate variability have led to greater input use and production expenses. Collectively, these trends demonstrate that climate change is intensifying pest and disease challenges, complicating sustainable fruit production.

Climate Change effect on pollination of Fruit Crops

Climate change is increasingly affecting pollinator activity and reproductive success in mango orchards, with direct consequences for fruit set and yield (Halder *et al.*, 2024) ^[13]. Mango relies heavily on insect pollinators—particularly bees, flies, and other small insects—for effective pollination. In India, rising temperatures, erratic rainfall, and unseasonal winds disturb pollinator behaviour by reducing their foraging time and survival. Extremely high temperatures during flowering can dry the stigmatic surface and reduce pollen viability, while low temperatures or rainy weather restrict insect movement (Singh *et al.*, 2025) ^[30]. These stresses are especially critical for major mango-growing belts such as Uttar Pradesh and Andhra Pradesh, where flowering often coincides with fluctuating spring weather.

In mango (*Mangifera indica*), successful pollination depends on synchronized flowering, active pollinator populations, and favorable temperature conditions, generally around 20-30 °C (Singh *et al.*, 2025) ^[30]. Climate variability can disrupt this synchronization by altering flowering time and reducing pollinator visits, leading to poor fertilization and heavy flower drop. High humidity and unseasonal rains during bloom may also promote fungal diseases that further reduce pollinator activity (Singh *et al.*, 2025) ^[30]. As a result, fruit set declines and yield becomes unstable. Strengthening pollinator conservation, encouraging managed bee colonies in orchards, and adopting climate-resilient management practices are essential to sustain mango productivity under changing climatic conditions.

In temperate fruit crops widely cultivated in northern and hill regions of India—such as apple, pear, plum, and cherry—the optimum temperature for pollination and fertilization lies below 15 °C. Deviations from this range, along with frequent spring rains and fog, negatively influence bee movement and pollen transfer (Singh *et al.*, 2025) ^[30]. For example, in apple orchards dominated by *Malus domestica*, extended cloudy or rainy conditions during bloom reduce bee visitation and stigmatic receptivity, resulting in weak fruit set. Similar pollination constraints are observed in pear and stone fruits grown in Himalayan valleys (Singh *et al.*, 2025) ^[30]. These climate-driven disturbances highlight the growing need in India to conserve pollinator populations, promote managed bee colonies, and adopt climate-resilient orchard practices to ensure stable fruit production (Halder *et al.*, 2024; Singh *et al.*, 2025) ^[13, 30].

Climate Change effect on dormancy and chilling requirement of Fruit Crops

Dormancy is an essential survival mechanism that protects sensitive plant tissues from unfavourable climatic conditions, but rapid climate change is threatening the adaptability of temperate fruit crops in India. Successful cultivation of many Indian temperate fruits depends on the fulfilment of specific winter chilling requirements, and mild

winters are increasingly causing insufficient chill accumulation. In crops such as apple, pear and cherry, lack of chilling leads to irregular bud break, uneven flowering, and poor fruit development, ultimately reducing yield and quality. Warming trends and the gradual loss of snow and ice cover in the Himalayas are further decreasing the natural chilling effect required for proper dormancy release. For high-chill cultivars requiring more than 1000 chilling hours, only a limited number of locations in India now provide suitable conditions, raising concerns about long-term sustainability and indicating a future need to replace existing cultivars with low-chill alternatives.

Climate Change effect on fruit quality of Fruit Crops

Rising temperatures associated with climate change are having a direct influence on fruit quality by altering the environmental conditions required for proper growth, ripening, and color development (Halder *et al.*, 2024) ^[13]. Even a moderate temperature increase of about 0.7-1.0 °C can shift the regions presently suitable for producing premium-quality mango varieties such as Dashehari and Alphonso (Nath *et al.*, 2018) ^[22]. Higher temperatures may also drastically reduce the areas favourable for red color development in guava, affecting its market appeal and consumer acceptance (Bakshi *et al.*, 2020) ^[4]. In citrus fruits like mandarin, exposure to high sunlight and temperatures around 35 °C produces fruits that are significantly firmer than those developing under cooler, shaded conditions, demonstrating how temperature variation affects texture and internal quality (Nath *et al.*, 2018) ^[22]. These changes are evident in major fruit-growing regions such as Uttar Pradesh and Maharashtra, where warming trends are already influencing fruit characteristics (Halder *et al.*, 2024) ^[13].

Elevated temperatures during fruit growth reduce the activity of key cell wall-modifying enzymes, slowing the natural ripening process and altering texture, flavor, and overall eating quality (Bakshi *et al.*, 2020) ^[4]. As a result, fruits may show delayed softening, uneven ripening, and compromised sensory traits. Such temperature-induced changes not only affect shelf life and postharvest behaviour but also reduce the commercial value of fresh produce (Halder *et al.*, 2024) ^[13]. Under Indian climatic conditions, maintaining optimal orchard microclimates through canopy management, irrigation, and protective practices is becoming increasingly important to preserve fruit quality in the face of ongoing climate warming (Nath *et al.*, 2018) ^[22].

Mitigation Strategies

Addressing climate change in horticulture requires a balanced strategy that integrates both adaptation and mitigation. Even if greenhouse gas emissions were drastically reduced today, global temperatures would continue to rise for several decades before stabilizing. If this warming trend accelerates unchecked, it could cross critical thresholds beyond which adaptation alone may not be sufficient to protect agricultural systems (Sthapit *et al.*, 2012) ^[32]. Therefore, combining mitigation efforts with adaptive strategies offers the most effective pathway to sustain fruit production under changing climatic conditions. One of the major concerns under climate change is the gradual erosion of plant genetic diversity, which limits the ability to develop new cultivars suited to emerging environments. The expansion of monoculture in horticulture has accelerated the loss of valuable genetic resources,

reducing the natural capacity of crops to cope with pests, diseases, and environmental stresses. Genetic diversity is the foundation of any crop improvement program, as diverse germplasm collections contain traits that can be used to breed varieties tolerant to abiotic and biotic stresses. Conserving and utilizing germplasm from a wide range of agro-climatic regions is essential for strengthening the resilience of the horticulture sector.

To secure future food and nutritional needs, plant genetic resources must be systematically conserved through both in situ and ex situ approaches. Effective collection, characterization, preservation, and management of germplasm will enable breeders and researchers to develop climate-resilient fruit varieties with improved productivity and quality. Protecting this genetic wealth is not only vital for present agricultural sustainability but also for ensuring that future generations have access to diverse and adaptable crop resources.

Climate-resilient fruit production increasingly depends on the adoption of location-specific strategies that integrate improved planting material with efficient orchard management. One of the most effective biological tools is the use of suitable rootstocks, which provide growers with options to enhance yield, fruit quality, and orchard efficiency. Carefully selected rootstocks help regulate tree vigour, shorten the juvenile phase, and support high-density planting systems. They also enable fruit crops to tolerate adverse soil and climatic conditions such as drought, salinity, flooding, and nutrient imbalances. For example, in grape cultivation, grafting commercial cultivars onto stress-tolerant rootstocks has been shown to improve water-use efficiency under moisture stress. Alongside rootstock selection, choosing climate-adapted cultivars is essential. Drought-tolerant fruit varieties such as Deanna and Excel fig, Arka Sahan annona, and Ruby pomegranate are better suited to high-temperature and water-limited environments. Similarly, mango cultivars differ in their tolerance to temperature extremes, while crops like aonla are recognized for their relative drought resilience, although young plants remain vulnerable to frost injury (Satisha *et al.*, 2006) [28].

Beyond varietal choice, orchard microclimate management plays a major role in climate adaptation. Resource-saving cultural practices such as mulching, fertigation, and fruit bagging help protect developing fruits from sunburn, cracking, and physiological disorders while improving fruit retention and quality. The application of anti-transpirants, including chitosan and kaolin, reduces heat stress by reflecting solar radiation and lowering leaf and fruit surface temperatures. These treatments have demonstrated improvements in fruit weight and overall yield in crops like banana and pomegranate. In addition, crop-specific climatic suitability must be considered: subtropical fruits such as litchi and longan require moderate warmth, whereas strictly tropical crops like rambutan are highly sensitive to cold stress. Matching crop and cultivar selection to regional climate conditions is therefore critical for stable production (More *et al.*, 2010) [21].

Dormancy avoidance techniques have been increasingly explored in India to compensate for inadequate winter chilling and to sustain the productivity of temperate fruit crops. Indian research has shown that artificial defoliation and rest-breaking treatments can help trees resume growth without fully meeting their natural chilling requirements. Studies conducted in temperate fruit belts of India,

particularly in regions such as Himachal Pradesh, report that post-harvest defoliation, followed by regulated irrigation and the application of rest-breaking chemicals, improves bud burst and flowering in crops like apple, pear, peach, plum, and apricot. Chemical defoliants such as zinc sulphate in peach and copper sulphate or urea in apple have been found effective in enhancing uniform bud sprouting under mild winter conditions. Indian experiments also indicate that late pruning combined with delayed irrigation can successfully manipulate bud break and flowering time, helping orchards adjust to warming winters. These dormancy-avoidance practices, supported by findings from Indian horticultural research articles, are becoming important adaptive strategies to maintain stable yields of temperate fruits under changing climatic conditions.

Long-term resilience of fruit systems also depends on strengthening soil health and enhancing carbon sequestration. Perennial fruit trees contribute more effectively to soil carbon storage than annual crops, helping mitigate greenhouse gas emissions while maintaining productivity under warmer conditions (Haldankar *et al.*, 2015) [12]. Practices such as organic manuring, residue incorporation, mulching, reduced tillage, and improving soil biodiversity enhance soil carbon reserves and moisture retention. Additional measures, including site-specific nutrient management and water-saving irrigation strategies, can be adopted by farmers with relatively low investment. Broader transitions—such as relocating production to climatically suitable zones or implementing incentive-supported conservation programs—may require policy backing. Together, these integrated approaches link adaptation with mitigation, creating a sustainable pathway for fruit production under changing climatic conditions.

Conclusion

Climate change is significantly reshaping fruit crop production systems worldwide. Rising temperatures and erratic rainfall intensify abiotic and biotic stresses in orchards. Phenological shifts disrupt flowering, pollination, and fruit set in many species. Fruit quality and yield stability are increasingly vulnerable to climatic extremes. Area suitability of major fruit crops is gradually shifting across regions.

Pest and disease dynamics are becoming more complex under warming conditions.

Conservation of genetic diversity is vital for developing resilient cultivars.

Adaptive orchard practices can reduce climate-related production risks.

Integrating mitigation with adaptation supports sustainable horticulture.

Long-term food security depends on climate-resilient fruit production systems.

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