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CLIMATE-SMART FRUIT PRODUCTION: STRATEGIES FOR A RESILIENT FUTURE

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ABSTRACT

Climate change is already affecting fruit production through increased temperatures, altered rainfall patterns, and accelerated frequency of extreme events. Fruit crops are particularly sensitive to these phenomena because of their perennial nature and specific climatic requirements. This paper reviews climate-smart strategies for fruit production, focusing on three pillars: adaptation, mitigation and improved resilience. Key strategies include climate-resilient cultivars, improved water management, soil and canopy management, diversified cropping systems, and low-emission practices with emphasis on simple, scientifically sound approaches that can be applied in smallholder and commercial systems.

Key words : Climate change, Fruit crops, Adaptation, Mitigation, Resilience, Climate-smart agriculture.

Introduction

Fruit crops are integral to global food and nutritional security, rural livelihoods and economic stability. Climate change is affecting agricultural productivity globally, and perennial fruit crops are especially vulnerable due to their long life cycle and fixed location in the field and their specific climatic requirements. (Rosenzweig *et al.*, 2014). Increased temperatures, erratic precipitation pattern, and more frequent heat waves, droughts, and frosts influence phenology, yield, fruit quality, and pest and disease pressure (Lobell *et al.*, 2011; Iglesias *et al.*, 2012), which ultimately results in flowering asynchrony, poor fruit set, sunburn cracking and shortened life span. Climate-smart agriculture (CSA) has been proposed as an integrated approach with three main objectives: sustainably increase productivity, enhance resilience, and reduce greenhouse gas (GHG) emissions wherever possible (FAO, 2013). Applying Climate Smart Agriculture (CAS) principles to fruit production can not only help secure yields but will also ensure quality while protecting natural resources. Achieving a resilient future demands a paradigm shift from conventional, input-intensive horticulture to knowledge-intensive strategies encompassing climate-

resilient cultivars, precision water and nutrient management, agroecological diversification, protected cultivation, digital decision-support tools, and policy-level risk mitigation (Singh *et al.*, 2013).

Climate Change Impacts on Fruit Production

Temperature increase and heat stress

Global mean surface temperature has already increased by about 1.1°C above pre-industrial levels and is assumed to rise further (IPCC, 2021). For many fruit crops, slight alteration in global temperature can change flowering time, shorten the duration of fruit development, and reduce fruit size and quality (Moriondo *et al.*, 2011). Studies have also highlighted that thermal stress induces reactive oxygen species (ROS) accumulation in fruit tissues, leading to cell membrane damage (Abobatta, 2021). Smith *et al.* (2022) found that sustained elevated temperatures suppressed photosynthetic efficiency and induced severe oxidative stress in perennial fruit crops. To contextualize these physiological responses, Garcia *et al.* (2021) confirmed that such abiotic stressors exacerbated phenological mismatches, ultimately destabilizing long-term orchard productivity and necessitating immediate varietal adaptation. It also exerts

significant negative impact in colour development along with berry shriveling. Reduced fruit set and increased flower drop in crops like mango and citrus (Singh *et al.*, 2013) are some common effects of heat stress in tropical fruit crops.

Changes in rainfall patterns and water stress

Many regions of Indian subcontinent are now experiencing more erratic rainfall and more intense droughts and floods (IPCC, 2021). Furthermore, precision irrigation and IoT-integrated soil sensors have demonstrated a significant potential to improve water-use efficiency by up to 35% in perennial orchards (Cosmulescu, 2026). Water shortage can have many negative impacts on fruit crops including excessive flower and fruit drop, fruit cracking, reduced fruit size, and ultimately reduction in the yield. Excess rainfall or poor drainage can lead to root hypoxia and disease such as *Phytophthora* root rot (Blum, 2011) especially in temperate fruit crops like apple, peach, cherries etc.

Chill accumulation and phenology shifts

Emerging research indicates that global warming-induced winter temperature shifts are increasingly disrupting dormancy-breaking mechanisms (MDPI, 2021). Chilling requirement is a crucial factor for flowering and fruiting of temperate crops. Temperate fruits like apple, pear, peach, apricot, and sweet cherry, require a certain amount of chill hours during winter to break dormancy. Warmer winters reduce chill accumulation, leading to delayed and non-uniform bud break, poor flowering, and ultimately reduced yield (Das *et al.*, 2025). Several studies project significant decline in suitable areas for high-chill cultivars under future climate scenarios (Darbyshire *et al.*, 2016).

Pests, diseases and invasive species

Climate change affects the life cycles, distribution, and abundance of pests and diseases. Warmer conditions can increase generation numbers per season of insects such as codling moth and fruit fly (Deutsch *et al.*, 2018), expand pest and pathogen ranges to higher latitudes and altitudes and alter plant susceptibility due to stress, increasing disease incidence (Bebber, 2015). For example, the spotted wing drosophila (*Drosophila suzukii*), a serious pest of soft fruits, has expanded in many regions with milder winters (Asplen *et al.*, 2015). Advanced tools like marker-assisted selection and genome editing rapidly develop cultivars with enhanced drought and pathogen tolerance (Antwi-Boasiako *et al.*, 2024). Utilizing robust rootstocks bolsters water-use efficiency (Koul *et al.*, 2022). Combining these adaptive agroecological practices ensures a sustainable trajectory for resilient fruit

production.

Extreme events (frosts, storms, heat waves)

Late spring frosts can severely damage flowers and young fruits, even in generally warmer climates, because phenological stages may advance earlier into frost-prone periods (Meier, 2018). Hailstorms can cause immediate fruit loss, while strong winds and heavy rainfall can lead to lodging, branch breakage, and soil erosion (Snyder and Melo-Abreu, 2005). Li *et al.* (2023) demonstrated that heat stress drastically altered endogenous phytohormone levels, leading to extensive flower abscission in orchards.

Climate-smart Fruit Production: Concept and Pillars

Climate-smart fruit production applies CSA principles to perennial horticultural systems. It aims to maintain or increase yield and fruit quality, strengthen resilience and adaptive capacity. Reduce or avoid GHG emissions and increase carbon sequestration where feasible. Achieving these goals requires integrated management of cultivars, orchards, water, soil, pests, and postharvest handling, together with supportive policies and extension services (FAO, 2013).

Adaptive Strategies for Climate-smart Fruit Systems

Climate-resilient cultivars and rootstocks

Cultivar and rootstock selection is one of the most powerful tools for adaptation in perennial systems.

Heat- and drought-tolerant cultivars

CRISPR/Cas-based genome editing is now accelerating the development of cultivars with targeted resilience to combined abiotic stresses (Li *et al.*, 2023 and Cabusora, 2024). For example: Some grapevine cultivars show better heat tolerance and maintain berry quality under higher temperatures (Carvalho *et al.*, 2015). Certain mango cultivars exhibit more stable flowering and fruiting under variable climates (Srivastava and Ram, 2019).

Low-chill cultivars

It is a very impressive strategy to avoid heat stress injury in temperate fruit crops. As warming winters threaten traditional dormancy cycles, the adoption of low-chill cultivars is critical. Recent evaluations demonstrate that these varieties can maintain market-preferred quality standards even when winter chill accumulation is significantly reduced (Herrera *et al.*, 2026). In temperate fruit species, low-chill cultivars can partially compensate for reduced winter chill (Campoy *et al.*, 2011). For instance, Low-chill peach varieties like- Flordasun, Flordaqueen, Pratap etc., and some nectarine cultivars have been developed and are increasingly planted in warm

winter areas (Sherman and Beckman, 2003). New apple cultivars like Anna, Tamma, Neomi, Schlomit etc with lower chill requirements are being evaluated for regions with warming winters (Luedeling *et al.*, 2011).

Stress-tolerant rootstocks

Rootstocks are increasingly being utilized to confer resistance to combined drought and salinity stress. New research indicates that optimized grafting technology between specific scions and stress-tolerant rootstocks enhances nutrient uptake efficiency under climate-induced soil stress (Singh *et al.*, 2026). In citrus, some rootstock species like Rangpur lime, Cleopatra Mandarin, and Trifoliate orange confer higher tolerance to water stress and soil salinity (Syvertsen and García-Sánchez, 2014), while Trifoliate orange, satsuma mandarin, kumquat show cold hardiness. In apples, Oranges and grapes, rootstock choice can influence vigour, phenology, and water-use efficiency (Atkinson *et al.*, 2013).

Orchard design and microclimate management

Site selection and orchard layout

Site Selection and Layout: Proper site selection remains the first line of defense against climate risks. Modern orchard management now utilizes high-resolution, sensor-integrated spatial mapping to identify sites with the lowest frost vulnerability and best natural drainage, which is essential for ensuring long-term tree health (Jahana *et al.*, 2026). North-facing or east-facing slopes of orchard in the Northern Hemisphere can reduce heat stress and sunburn in some situations. Higher tree density with suitable training systems can improve light distribution and reduce excessive heat load on fruits (Corelli Grappadelli and Lakso, 2007).

Shade nets and protective covers

Shade nets, hail nets, and photosensitive covers can reduce solar radiation, lower canopy temperatures, and protect against hail and birds (Shahak, 2014). Recent trials on spectral-selective netting prove that it not only protects fruit from heat-induced sunburn, but also dynamically optimizes anthocyanin synthesis for improved color profile (Mupambi *et al.*, 2018). Studies in apples and pears show that nets reduce sunburn incidence and improve fruit color uniformity (Iglesias, 2006). Plastic covers and “rain shelters” in cherries and berries can reduce cracking during heavy rainfall events (Lang, 2009).

Windbreaks and agroforestry

Integrated agroforestry windbreaks are now being optimized to reduce mechanical damage from extreme wind events while simultaneously improving the microclimate for pollinators during critical flowering

windows (Bentrup *et al.*, 2019). Integrating trees with fruit crops in agroforestry systems may also buffer microclimate, increase biodiversity, and sequester carbon (Jose, 2009). However, competition for light and water must be managed through appropriate spatial design.

Water management and irrigation strategies

Efficient irrigation systems

Modern precision irrigation systems utilize cloud-based data to automate water delivery, which significantly increases water-use efficiency (Anandha Jothi *et al.*, 2026). Drip and subsurface technologies ensure water is delivered directly to the root zone, minimizing surface evaporation (Gorthi *et al.*, 2025) as it has the capacity to deliver water in the root zone by 90% efficiency. Micro-sprinkler also has higher water-use efficiency compared with surface irrigation (Feres and Soriano, 2007). They allow precise application of water and facilitate fertigation. A shift from flood to drip irrigation can save 30–50% water without yield loss in many fruit crops, including citrus and grapes (Chaves *et al.*, 2010).

Regulated deficit irrigation (RDI)

RDI is increasingly used as a strategic tool to conserve water during specific phenological stages (Li *et al.*, 2023). RDI intentionally applies less water than full crop evapotranspiration requirement during specific but non-critical phenological stages that are less sensitive to stress to minimize water use. Recent trials indicate that well-timed deficit irrigation can enhance fruit quality by promoting the synthesis of secondary metabolites (Lara *et al.*, 2020). This can save water and, in some cases, improve fruit quality (for example higher sugar concentration or better fruit color) without reducing yield significantly (Girona *et al.*, 2006). Grapevine, olive and some stone fruits like peach, plum etc also respond positively to well-timed deficit irrigation (Chaves *et al.*, 2010).

Rainwater harvesting and water storage

On-farm water harvesting such as ponds, reservoirs, or farm dams increases water availability during dry periods and buffers rainfall variability (Rockström *et al.*, 2010). Rainwater harvesting provides a reliable buffer against rainfall variability, especially for small-scale orchard sustainability new modular storage designs have increased the accessibility of these systems for rural fruit production. Roof water harvesting from farm buildings and greenhouses can supplement irrigation, especially in smallholder systems (Amos *et al.*, 2026).

Soil moisture monitoring and decision support

Wireless sensor networks now allow for real-time

monitoring of soil moisture, enabling irrigation decisions based on plant-specific needs. Integrating these sensors with region-specific models provides high-throughput data that significantly improves evapotranspiration predictions (Zhang *et al.*, 2025). Using soil moisture sensors, tensiometers, and simple water balance models helps farmers apply irrigation only when needed (Feres and Soriano, 2007). Digital decision support tools that integrate weather forecasts and crop models are increasingly available and can guide irrigation scheduling to improve both water savings and yield stability.

Soil and groundcover management

Organic matter and soil structure

Increasing soil organic carbon is essential to improve water-holding capacity and resilience against drought (Oyebiyi *et al.*, 2026). Long-term applications of organic amendments enhance soil structure and provide a buffer for nutrient availability in perennial systems (Munna *et al.*, 2026). Application of composts, animal manures, and mulches can enhance soil structure and resilience to drought and heavy rainfall.

Mulching

Mulching plays a critical role in climate resilience strategy in fruit crop production by conserving soil moisture, regulating root zone temperature and reducing water evaporation to a great extent. Organic mulches, such as agricultural residues and synthetic films act as effective microclimate regulators that mitigate soil moisture evaporation, moderate soil temperature and suppress weed proliferation, which significantly enhances fruit quality and overall yield in orchard systems (Mohammed *et al.*, 2026).

Cover crops

Cover crops between tree rows protect soil from erosion, increase infiltration, and contribute organic matter and nitrogen (Hartwig and Ammon, 2002). Mulching helps regulate root zone temperatures and conserves soil moisture during heat waves (Kader *et al.*, 2017). Cover crops protect the soil from erosion and improve infiltration; however, species selection is vital to ensure they do not compete with fruit trees for water. Innovative “living mulch” systems are now being refined to minimize this competition while maintaining soil biodiversity (Vandana *et al.*, 2023).

Integrated pest and disease management (IPM) under climate change

IPM will be critical under changing climates. Key components include:

- Monitoring pest and disease populations and using thresholds for control actions.
- Biological control through natural enemies.
- Cultural practices such as pruning, sanitation, and cultivar choice.
- Targeted use of pesticides with minimal environmental impact (Barzman *et al.*, 2015).

Climate change may require adjustments in spraying calendars and new forecasting models that consider temperature-driven pest development (Bebber, 2015). IPM integrates monitoring, biological control, and cultural practices to minimize synthetic pesticide use (Barzman *et al.*, 2015). Because climate change alters the life cycles of insects and pathogens, new IPM protocols rely on real-time, temperature-driven forecasting models to predict outbreaks (Miller *et al.*, 2025).

Diversification and risk management

Crop and Varietal Diversification: Diversifying species and cultivars is a fundamental risk-spreading strategy, as it reduces the likelihood of total crop failure due to extreme weather. Integrating early and late-ripening varieties ensures a more stable market supply throughout the season (Khanam *et al.*, 2018).

Mixed Systems and Livestock Integration: Integrating small-scale livestock with fruit production creates a circular nutrient system, recycling waste and diversifying income streams. These systems provide superior economic resilience against climate and market-related shocks (Peterson *et al.*, 2026).

Mitigation Co-Benefits in Fruit Production

Soil carbon sequestration

Increasing soil organic matter (SOM) is essential to improve water-holding capacity and resilience against drought. Long-term applications of organic amendments, such as compost and biochar, enhance soil structure and provide a buffer for nutrient availability in perennial systems (Oyebiyi *et al.*, 2026). Some studies showed that orchard systems can accumulate significant soil carbon, especially under grass cover and minimal soil disturbance (Guo and Gifford, 2002). Furthermore, the integration of “living mulches” or cover crops can be optimized to minimize competition with fruit trees while maintaining soil biodiversity and preventing erosion (Sanchez *et al.*, 2026).

Reduced emissions from inputs and energy use

Efficient use of nitrogen fertilizers through soil testing, fertigation, and split applications lowers nitrous oxide emissions (Butterbach-Bahl *et al.*, 2013). Reducing the

carbon footprint of orchard operations involves transitioning to “water-smart” agriculture. Digital tools, including IoT-based soil-moisture monitoring and AI-driven irrigation scheduling, allow for precise resource allocation, which significantly reduces the energy required for pumping and the emissions associated with nitrogen fertilizer leaching (Sellami *et al.*, 2026). Additionally, shifting toward renewable energy for cold storage and irrigation automation is a primary strategy for lowering operational emissions (Anadha Jothi *et al.*, 2026). Using energy-efficient pumps, renewable energy (for example solar-powered irrigation), and optimizing cold storage can reduce CO₂ emissions associated with fruit production and postharvest handling (Pathak *et al.*, 2010).

Improved postharvest management

Improved postharvest management is another benefit of climate resilient fruit production. Postharvest losses in fruit supply chains are often high, especially in tropical regions without reliable cold chains. Postharvest losses are exacerbated by climate-induced physiological stress. Modern strategies now prioritize edible coatings—derived from biodegradable polymers—which regulate gas exchange, reduce water loss and postpone ripening, thereby extending shelf life without synthetic chemical reliance (Pellegrino *et al.*, 2024). Improving maturity-driven harvest timing also significantly reduces economic losses and resource waste, as fruit quality directly influences the net return per hectare (Judijanto *et al.*, 2026).

Case studied of Climate-smart Fruit Production Strategies

Mediterranean fruit orchards

Mediterranean regions face hotter and drier summers, with declining water availability. Climate-smart practices adopted include transition to drip irrigation and deficit irrigation in olives, citrus, and grapes (Chaves *et al.*, 2010). Use of shade nets in apples and pears to reduce sunburn and water use (Iglesias, 2006). Modeling studies suggested that combining deficit irrigation with mulching and improved cultivars can maintain yields under projected climate scenarios while reducing water use (Moriondo *et al.*, 2011). These systems face increasing drought intensity. Adaptive strategies including utilization of drought-resilient rootstocks and implementing regulated deficit irrigation (RDI) have the ability to manage water stress while maintaining fruit quality (Rahman *et al.*, 2025).

Temperate pome fruit under warming winters

Warming winters are disrupting chilling requirements

in pome fruits. Mitigation involves the use of dormancy-breaking agents and selecting low-chill cultivars to stabilize production despite unpredictable spring frosts (Rahman *et al.*, 2025). In many temperate zones, apple and pear growers are already seeing reduced winter chill and irregular flowering (Luedeling *et al.*, 2011). Adaptation responses include: Gradual replacement of high-chill cultivars with low- or medium-chill types (Darbyshire *et al.*, 2016), use of rest-breaking agents, although these raise concerns about environmental and health impacts (Campoy *et al.*, 2011), establishing orchards to higher elevations where chill remains adequate, decision tools that model future chill accumulation help growers and breeders plan long-term cultivar strategies (Luedeling *et al.*, 2011).

Tropical fruit systems

Tropical fruit such as mango, banana and citrus are sensitive to changes in rainfall and increased frequency of storms and cyclones (Srivastava and Ram, 2019). Climate-smart actions include improved drainage, windbreaks, and staking to reduce damage from storms, mulching and cover crops to retain soil moisture during dry spells, introduction of more drought-tolerant cultivars and rootstocks. Adoption of integrated nutrient and water management to maintain productivity under erratic rainfall (Jain *et al.*, 2024).

Research Gaps and Future Directions

Key research needs include:

Breeding of fruit cultivars and rootstocks with combined tolerance to heat, drought, and biotic stresses, and with lower chill requirements where needed improved understanding of tree physiology under multiple stresses (heat, water deficit, salinity) to optimize irrigation and canopy management (Campoy *et al.*, 2011). Multi-year, systems-level trials of integrated climate-smart practices in different agro-ecological zones. Better models that link climate projections, phenology, pests and yield for main fruit species. Socioeconomic studies on adoption barriers, cost-benefit analysis, and gender dimensions of climate-smart fruit interventions. (Chaves *et al.*, 2010).

Conclusion

Climate change was already affecting fruit production through altered temperatures, erratic rainfall patterns and extreme events, with assumed further changes. Climate-smart fruit production offered a practical framework for adaptation while contributing to mitigation. Core strategies include use of climate-resilient cultivars and rootstocks, improved water and soil management, microclimate modification through nets and covers, integrated pest

management and diversified production systems. Adoption of these practices can improve resilience of fruit systems and stabilize yields, especially when supported by strong extension services, appropriate policies, and access to finance. Continued research and innovation, combined with farmer participation, will be essential to build fruit production systems that are productive, climate-resilient, and environmentally sustainable.

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