



E-ISSN: 2663-1067

P-ISSN: 2663-1075

NAAS Rating (2026): 4.74

www.hortijournal.com

IJHFS 2026; 8(7): 101-110

Received: 18-04-2026

Accepted: 22-05-2026

Amol M Virkar

Department of Horticulture,
Chhatrapati Shivaji Maharaj
Krishi Vidnyan Sankul,
Kashti, MPKV, Rahuri,
Maharashtra, India

Vipul V Mali

Department of Horticulture,
Chhatrapati Shivaji Maharaj
Krishi Vidnyan Sankul,
Kashti, MPKV, Rahuri,
Maharashtra, India

Vipul K Bhiram

Department of Horticulture,
Mahatma Phule Krishi
Vidyapeeth, Rahuri,
Maharashtra, India

Vaishnavi A Dolas

Department of Horticulture,
Mahatma Phule Krishi
Vidyapeeth, Rahuri,
Maharashtra, India

Bhushan N Ralebhat

Department of Horticulture,
Mahatma Phule Krishi
Vidyapeeth, Rahuri,
Maharashtra, India

Corresponding Author:

Amol M Virkar

Department of Horticulture,
Chhatrapati Shivaji Maharaj
Krishi Vidnyan Sankul,
Kashti, MPKV, Rahuri,
Maharashtra, India

Climate change-induced physiological disorders in fruit crops: Mechanisms, impacts, and mitigation strategies

Amol M Virkar, Vipul V Mali, Vipul K Bhiram, Vaishnavi A Dolas and Bhushan N Ralebhat

DOI: <https://www.doi.org/10.33545/26631067.2026.v8.i7b.804>

Abstract

Climate change is increasingly influencing the productivity, quality, and sustainability of fruit production systems through the intensification of abiotic stresses such as heat waves, drought, erratic precipitation, elevated solar radiation, and chilling-related events. These climatic disturbances are contributing to a rising incidence of physiological disorders that adversely affect fruit growth, marketability, storage life, and economic returns. This review synthesizes current knowledge on the mechanisms, impacts, and mitigation strategies associated with climate change-induced physiological disorders in fruit crops. Major disorders, including fruit cracking, bitter pit, chilling injury, internal browning, sunburn, russetting, and premature fruit drop, are examined in relation to their climatic drivers and underlying physiological responses. The evidence indicates that climate-induced disruptions in water relations, calcium transport and partitioning, hormonal signaling, photosynthetic efficiency, carbohydrate metabolism, membrane stability, and reactive oxygen species homeostasis play central roles in disorder development. Furthermore, the increasing occurrence of compound stress conditions, particularly combinations of drought, heat, and excessive irradiance, often amplifies physiological damage beyond the effects of individual stressors. The review highlights the importance of integrated mitigation approaches encompassing climate-smart orchard management, precision irrigation, balanced mineral nutrition, canopy and microclimate modification, improved postharvest handling, and the development of stress-resilient cultivars. Emerging technologies, including remote sensing, artificial intelligence, molecular diagnostics, and precision horticulture, are also discussed as promising tools for early detection and proactive management. Overall, enhancing the resilience of fruit production systems will require multidisciplinary strategies that integrate physiological, agronomic, genetic, and technological innovations to sustain fruit quality and productivity under increasingly variable climatic conditions.

Keywords: Climate change, fruit crops, physiological disorders, abiotic stress, fruit cracking, bitter pit, chilling injury, climate resilience, precision horticulture, sustainable fruit production

Introduction

Fruit crops constitute some of the most valuable components of global agriculture and human nutrition, providing essential vitamins, minerals, dietary fiber, antioxidants, and bioactive compounds. However, fruit production systems are highly sensitive to environmental fluctuations because critical processes such as flowering, fruit set, fruit enlargement, mineral accumulation, ripening, and postharvest physiology are closely regulated by climatic conditions (Atkinson & Urwin, 2012; IPCC, 2023) ^[1, 10]. Consequently, climate change has emerged as one of the most significant challenges facing modern horticulture, with rising temperatures, altered precipitation patterns, prolonged droughts, and increasing frequency of extreme weather events adversely affecting fruit yield and quality worldwide (Lesk *et al.*, 2016; IPCC, 2023) ^[14, 10].

Unlike annual crops, perennial fruit trees are exposed to climatic variability over multiple growing seasons. Repeated exposure to environmental stresses can alter tree vigor, canopy architecture, source-sink relationships, water-use efficiency, and mineral transport processes, thereby increasing susceptibility to physiological disorders (Atkinson & Urwin, 2012; Hatfield & Prueger, 2015) ^[1, 9]. These disorders often develop independently of pathogenic organisms and may manifest as fruit cracking, sunburn, bitter pit, internal browning, chilling

injury, premature fruit drop, and other quality-related defects. Their economic significance is substantial because even minor cosmetic or internal defects can render fruit unmarketable, resulting in reduced profitability, increased postharvest losses, and shortened storage life (Kalcsits *et al.*, 2017; Lurie & Crisosto, 2005) ^[11, 15]. Recent advances in plant stress physiology have significantly improved understanding of how drought, heat stress, chilling stress, and compound abiotic stresses affect fruit development and quality. Research has demonstrated that climate-induced stresses disrupt plant water relations, calcium transport, photosynthetic performance, hormonal regulation, redox homeostasis, and carbohydrate metabolism, thereby increasing the likelihood of physiological disorder development (Zandalinas *et al.*, 2020; Moretti *et al.*, 2010) ^[22, 18]. Furthermore, growing evidence suggests that combined or sequential stress events often produce more severe physiological consequences than individual stresses acting alone, emphasizing the need for integrated approaches to climate resilience in horticultural systems (Mittler, 2006; Zandalinas *et al.*, 2020) ^[17, 22]. Given the increasing vulnerability of fruit production systems to climate variability, a comprehensive synthesis of current knowledge is needed to better understand the links between climate change and physiological disorder

development. Therefore, this review examines the major climate change-induced physiological disorders affecting fruit crops, explores the underlying physiological and biochemical mechanisms, evaluates their impacts on fruit quality and productivity, and discusses current and emerging mitigation strategies for developing climate-resilient horticultural production systems. The occurrence and severity of physiological disorders in fruit crops are increasingly influenced by climate change-driven abiotic stresses, including heat waves, drought, erratic rainfall, elevated solar radiation, and chilling events. These stresses disrupt key physiological processes such as water balance, calcium transport, photosynthesis, membrane stability, hormonal regulation, and oxidative metabolism, resulting in a range of quality-limiting disorders. As summarized in Table 1, major climate change-induced physiological disorders—including fruit cracking, bitter pit, chilling injury, internal browning, sunburn, russetting, and premature fruit drop—are associated with distinct climatic triggers, physiological mechanisms, and characteristic symptoms. Understanding these relationships is essential for developing effective mitigation strategies and improving the resilience of fruit production systems under changing climatic conditions.

Table 1: Major Climate Change-Induced Physiological Disorders in Fruit Crops, Causes, and Symptoms

Disorder	Major Climatic Trigger(s)	Key Physiological Cause	Major Symptoms
Fruit cracking	Drought followed by rainfall/irrigation	Rapid water uptake and skin rupture	Fruit splitting and cracking
Bitter pit	Heat stress, drought, irregular moisture	Localized calcium deficiency	Sunken dark spots and corky tissue
Chilling injury	Low non-freezing temperatures	Membrane damage and oxidative stress	Pitting, discoloration, uneven ripening
Internal browning	Chilling stress, prolonged storage	Cellular breakdown and oxidation	Internal tissue browning
Sunburn	High temperature and solar radiation	Photooxidative and heat damage	Necrotic or discolored fruit surface
Premature fruit drop	Heat and drought stress	Hormonal imbalance and stress-induced abscission	Early fruit shedding
Russetting	Humidity fluctuations and rainfall	Cuticle cracking and suberization	Rough, corky fruit skin
Watercore	High temperature during maturation	Abnormal sugar and water accumulation	Glassy, translucent flesh
Fruit shriveling	Drought and heat stress	Excessive water loss	Wrinkled and dehydrated fruits
Uneven ripening	Temperature fluctuations and heat stress	Disrupted ethylene and carbohydrate metabolism	Non-uniform color and softening

Source: Atkinson and Urwin (2012) ^[1], De Freitas and Mitcham (2012) ^[3], Lurie and Crisosto (2005) ^[15], Kalcsits *et al.* (2017) ^[11], Wang *et al.* (2023) ^[27], Moretti *et al.* (2010) ^[18], and Zandalinas *et al.* (2020) ^[22].

Review Methodology

Literature Search Strategy

This review was conducted using a PRISMA-inspired narrative review framework to systematically synthesize current knowledge on climate change-induced physiological disorders in fruit crops. The literature search focused on five major thematic areas: climate change, fruit crops, abiotic stress, physiological disorders, and mitigation strategies. Comprehensive searches were performed across major scientific databases, including Scopus, Web of Science, PubMed, ScienceDirect, SpringerLink, Wiley Online Library, and Google Scholar. Search terms were selected based on recurring concepts identified in recent reviews and primary research articles and included combinations of the following keywords: climate change, fruit crops, abiotic stress, drought stress, heat stress, combined drought and heat stress, physiological disorders, fruit cracking, bitter pit, sunburn, chilling injury, calcium transport, reactive oxygen species (ROS), oxidative stress, sugar signaling, fruit quality, and climate resilience. Boolean operators (AND, OR) were used to optimize search sensitivity and specificity. The search primarily covered

literature published between 2010 and 2025, with particular emphasis on studies published after 2015 to ensure incorporation of the most recent advances in fruit stress physiology, postharvest biology, and climate adaptation research (Page *et al.*, 2021; IPCC, 2023) ^[20, 10].

Inclusion and Exclusion Criteria

- Studies were included if they met the following criteria:
1. Published in peer-reviewed scientific journals.
 2. Focused on fruit crops, fruit-tree physiology, postharvest physiology, or physiological disorders associated with abiotic stress.
 3. Examined the mechanisms, impacts, or management of climate-related stresses, including drought, heat, chilling, water deficit, high irradiance, or compound stress conditions.
 4. Provided experimental, observational, mechanistic, or review-based evidence directly relevant to physiological disorder development or mitigation.

Studies were excluded if they

1. Were non-peer-reviewed publications, editorials,

- opinion articles, or conference abstracts lacking complete experimental information.
2. Originated from predatory or non-indexed journals.
 3. Focused exclusively on field crops or unrelated plant

4. Presented insufficient methodological detail or unsupported conclusions.

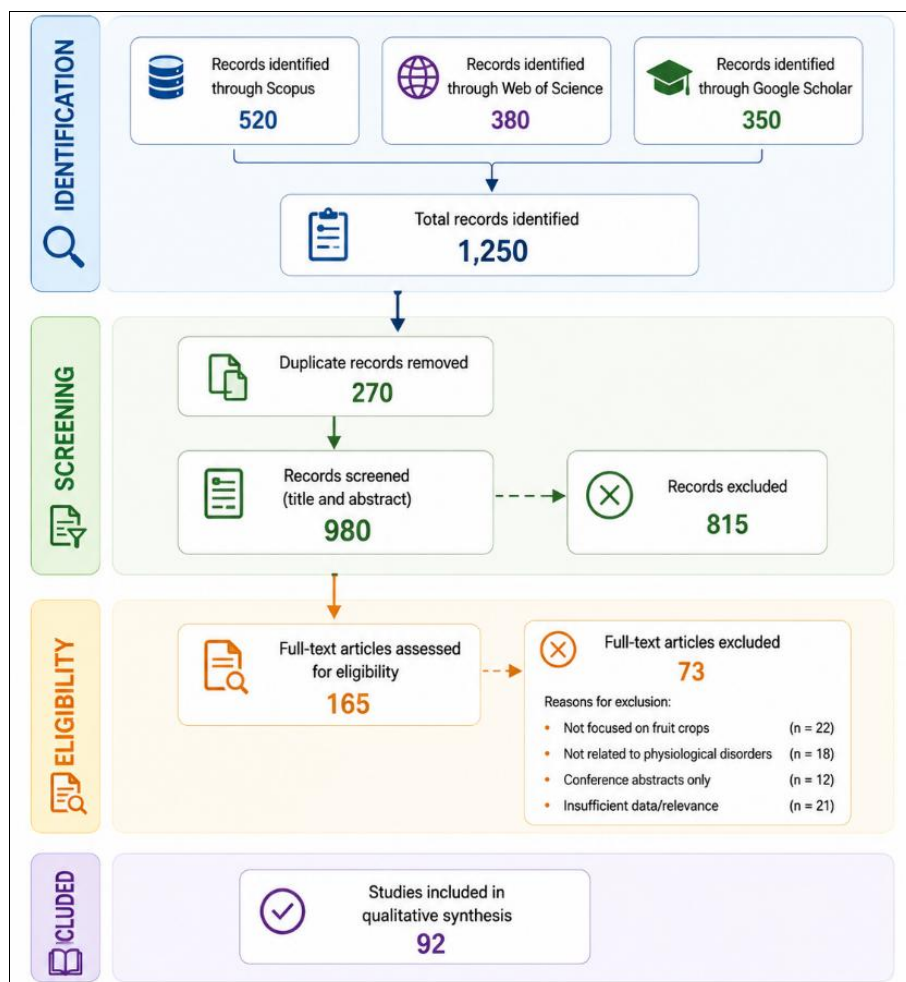


Fig 1: PRISMA-inspired flow diagram of literature search and study selection process

Data Extraction and Quality Assessment

Relevant information was extracted from each eligible study, including crop species, stress factor, physiological disorder, developmental stage affected, underlying physiological and biochemical mechanisms, impacts on fruit quality, and mitigation strategies. Additional information regarding experimental design, environmental conditions, and key outcomes was recorded when available.

The quality and relevance of each study were assessed based on journal reputation, methodological rigor, clarity of experimental design, statistical robustness, and relevance to fruit crop systems. Greater emphasis was placed on studies providing mechanistic insights, field-scale validation, postharvest evaluations, and translational applications relevant to climate-resilient horticultural production. Priority was also given to recent review articles and landmark studies that have significantly advanced understanding of fruit responses to abiotic stress and physiological disorder development.

Study Selection Process

The study selection process followed the general principles of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework (Page *et al.*, 2021) [20]. Records identified through database searches

were screened based on title, abstract, and full-text evaluation. Duplicate records were removed prior to eligibility assessment. Studies meeting the predefined inclusion criteria were retained for qualitative synthesis and thematic analysis.

PRISMA Flow Diagram

A formal PRISMA flow diagram should be prepared following completion of the final database search and screening process. The diagram should include:

- Records identified through database searching.
- Records remaining after duplicate removal.
- Records screened by title and abstract.
- Full-text articles assessed for eligibility.
- Studies included in the qualitative synthesis.
- Studies excluded at each stage with reasons for exclusion.

The present review is primarily based on peer-reviewed articles indexed in internationally recognized databases and emphasizes recent advances in climate stress physiology, fruit physiological disorders, postharvest biology, and climate-resilient horticultural management.

Climate Change and Fruit Crop Production

Climate change is increasingly recognized as a major constraint on sustainable fruit production worldwide. Its effects extend beyond gradual increases in average temperature and encompass more frequent and intense heat waves, prolonged drought periods, irregular precipitation patterns, elevated solar radiation, and compound stress events occurring during critical phenological stages. These environmental changes directly influence stomatal conductance, photosynthetic efficiency, reproductive development, fruit set, and tissue integrity, while indirectly affecting nutrient transport, canopy energy balance, and overall orchard productivity (Hatfield & Prueger, 2015; IPCC, 2023) ^[9, 10].

Fruit crops are particularly vulnerable because reproductive processes and fruit development are highly sensitive to environmental fluctuations. Climatic stress occurring during flowering, pollination, fertilization, or early fruit growth can significantly reduce yield and fruit quality. Furthermore, increasing climate variability has intensified the occurrence of physiological disorders that compromise marketability, storage potential, and economic returns (Atkinson & Urwin, 2012; Zandalinas *et al.*, 2020) ^[1, 22].

Drought Stress and Fruit Production

Drought remains one of the most extensively studied abiotic stresses affecting fruit crops. Water deficit adversely influences vegetative growth, flowering, fruit development, nutrient uptake, and overall productivity. At the physiological level, drought stress triggers complex adaptive responses involving abscisic acid (ABA) signaling, calcium-mediated signaling pathways, reactive oxygen species (ROS) regulation, transcriptional reprogramming, and microRNA-mediated gene expression control (Osakabe *et al.*, 2014; Moretti *et al.*, 2010) ^[19, 18].

In perennial fruit crops, the consequences of drought extend beyond immediate reductions in growth. Water deficits alter hydraulic conductivity, root-to-shoot communication, carbon allocation patterns, and fruit sink strength, thereby affecting fruit size, mineral composition, and susceptibility to physiological disorders. Repeated drought episodes may also induce long-term changes in orchard performance and stress memory, influencing productivity across multiple growing seasons (Atkinson & Urwin, 2012; Chaves *et al.*, 2010) ^[1, 2].

Heat Stress and Compound Climate Stressors

Heat stress has emerged as a critical threat to fruit production, particularly in regions experiencing recurrent extreme temperature events. Elevated temperatures disrupt photosynthesis, respiration, pollen viability, fruit set, and cellular membrane stability, ultimately reducing fruit yield and quality (Hatfield & Prueger, 2015) ^[9]. However, under field conditions, heat stress rarely occurs in isolation and is frequently accompanied by drought, creating compound stress scenarios that produce more severe physiological consequences than either stress alone.

Recent studies have demonstrated that combined heat and drought stress can exert non-additive effects on plant metabolism. Under such conditions, hormonal regulation, stomatal behavior, ROS homeostasis, carbohydrate metabolism, and energy balance become increasingly dysregulated, leading to greater reductions in growth, productivity, and fruit quality than predicted from single-

stress responses (Mittler, 2006; Zandalinas *et al.*, 2020) ^[17, 22].

In citrus and other evergreen fruit species, the simultaneous occurrence of drought, high temperature, and excessive solar radiation has been shown to impair photosystem II activity, disrupt redox homeostasis, increase oxidative damage, and reduce net photosynthetic rates. These findings highlight how multiple climate-related stressors converge to influence fruit-tree physiology and increase the risk of physiological disorder development under future climate scenarios (Guidi *et al.*, 2019; Zandalinas *et al.*, 2020) ^[7, 22].

Major Physiological Disorders

Fruit Cracking

Fruit cracking is among the most economically important climate-sensitive physiological disorders affecting fleshy fruits. The disorder results from complex interactions among fruit growth dynamics, water relations, cuticular characteristics, epidermal elasticity, and environmental conditions. Rapid fluctuations in water availability frequently generate excessive internal pressure within fruit tissues, exceeding the mechanical strength of the skin and resulting in cracking (Knoche & Lang, 2017) ^[12].

Fruit cracking has been widely reported in sweet cherry, apple, pomegranate, litchi, jujube, grape, and several other fruit crops. Economic losses arise not only from direct fruit splitting but also from increased susceptibility to microbial infection, reduced storage life, and diminished market quality (Knoche & Lang, 2017; Knoche *et al.*, 2018) ^[12, 13]. Climatic conditions characterized by prolonged drought followed by heavy rainfall or excessive irrigation are particularly conducive to cracking because rapid water uptake alters fruit turgor pressure and disrupts normal tissue integrity.

Bitter Pit and Calcium-Related Disorders

Bitter pit is one of the most extensively studied physiological disorders in apple and serves as a model system for understanding climate-related mineral imbalances in fruit crops. Traditionally, the disorder has been associated with localized calcium deficiency within fruit tissues. However, contemporary research indicates that calcium concentration alone cannot fully explain bitter pit incidence and severity (Kalsits *et al.*, 2017) ^[11].

Current evidence suggests that bitter pit development is influenced by a complex interaction of factors, including cultivar genetics, rootstock characteristics, fruit growth rate, transpiration dynamics, xylem functionality, calcium partitioning, and the spatial distribution of calcium within fruit tissues (Kalsits *et al.*, 2017; De Freitas & Mitcham, 2012) ^[11, 3]. Climate change is expected to exacerbate these factors because drought and heat stress can reduce xylem flow, alter transpiration patterns, and disrupt mineral transport processes, thereby increasing the likelihood of fruit-level calcium imbalances even when soil nutrient availability is adequate. Consequently, bitter pit should be viewed as a multifactorial physiological disorder arising from interactions among environmental conditions, plant physiology, and genetic predisposition rather than as a simple manifestation of calcium deficiency alone.

Chilling Injury and Internal Browning Syndromes

Chilling injury is one of the most important postharvest physiological disorders affecting tropical, subtropical, and

certain temperate fruit species exposed to non-freezing but suboptimal low temperatures during storage and transportation. The disorder is particularly prevalent in fruits such as mango, banana, papaya, avocado, citrus, peach, nectarine, and pear, where cold storage temperatures below species-specific thresholds disrupt normal cellular metabolism and physiological functioning (Lurie & Crisosto, 2005; Wang *et al.*, 1990) [15, 26].

Current evidence indicates that chilling injury is a complex physiological syndrome rather than a simple response to low-temperature exposure. The disorder involves membrane lipid phase transitions, excessive reactive oxygen species (ROS) accumulation, mitochondrial dysfunction, impaired energy metabolism, and alterations in hormonal signaling pathways. These disturbances ultimately result in visible symptoms such as surface pitting, peel discoloration, uneven ripening, internal browning, water-soaked tissues, mealiness, and accelerated quality deterioration during subsequent shelf-life periods (Valenzuela *et al.*, 2017; Wang *et al.*, 1990) [24, 26].

In pome and stone fruits, chilling-related physiological disorders include superficial scald in apples and pears, internal browning, flesh breakdown, mealiness, woolliness, and texture deterioration in peaches and nectarines. These disorders significantly reduce consumer acceptance, storage potential, and commercial value, thereby representing a major challenge for modern fruit supply chains (Lurie & Crisosto, 2005; Valenzuela *et al.*, 2017) [15, 24].

Sunburn, Fruit Drop, Russeting, and Other Climate-Related Disorders

In addition to fruit cracking, bitter pit, and chilling injury, climate change has increased the incidence of several other economically important physiological disorders, including sunburn, premature fruit drop, russeting, and skin blemishes. Elevated air temperatures, excessive solar radiation, water

deficit, and altered canopy microclimates are among the primary environmental factors contributing to these disorders (Glenn *et al.*, 2002) [6].

Sunburn develops when fruit surface temperatures exceed critical physiological thresholds, causing cellular damage, chlorophyll degradation, membrane disruption, and tissue necrosis. High solar irradiance combined with elevated ambient temperature can substantially increase fruit surface temperature above air temperature, making sunburn particularly problematic under climate warming scenarios.

Similarly, drought stress and heat stress can accelerate premature fruit abscission through alterations in hormonal balance, particularly involving abscisic acid (ABA), ethylene, and auxin signaling pathways. Russeting and other skin disorders are also influenced by environmental fluctuations that affect cuticle formation, epidermal integrity, and fruit surface development. Although symptom expression varies among species, these disorders share common physiological origins involving oxidative stress, disrupted carbon allocation, membrane instability, and altered stress signaling networks (Glenn *et al.*, 2002; Atkinson & Urwin, 2012) [6, 1].

Physiological and Biochemical Mechanisms Underlying Climate Change-Induced Disorders

Climate change-induced physiological disorders arise when environmental stress exceeds the capacity of fruit crops to maintain cellular homeostasis, hydraulic functionality, metabolic balance, and reproductive stability. Across diverse fruit species, abiotic stresses such as drought, heat, chilling, and excessive radiation converge on several interconnected physiological pathways, including water relations, hormonal regulation, calcium signaling, reactive oxygen species metabolism, photosynthesis, carbohydrate partitioning, and stress-responsive gene networks (Mittler, 2006; Zandalinas *et al.*, 2020) [17, 22].

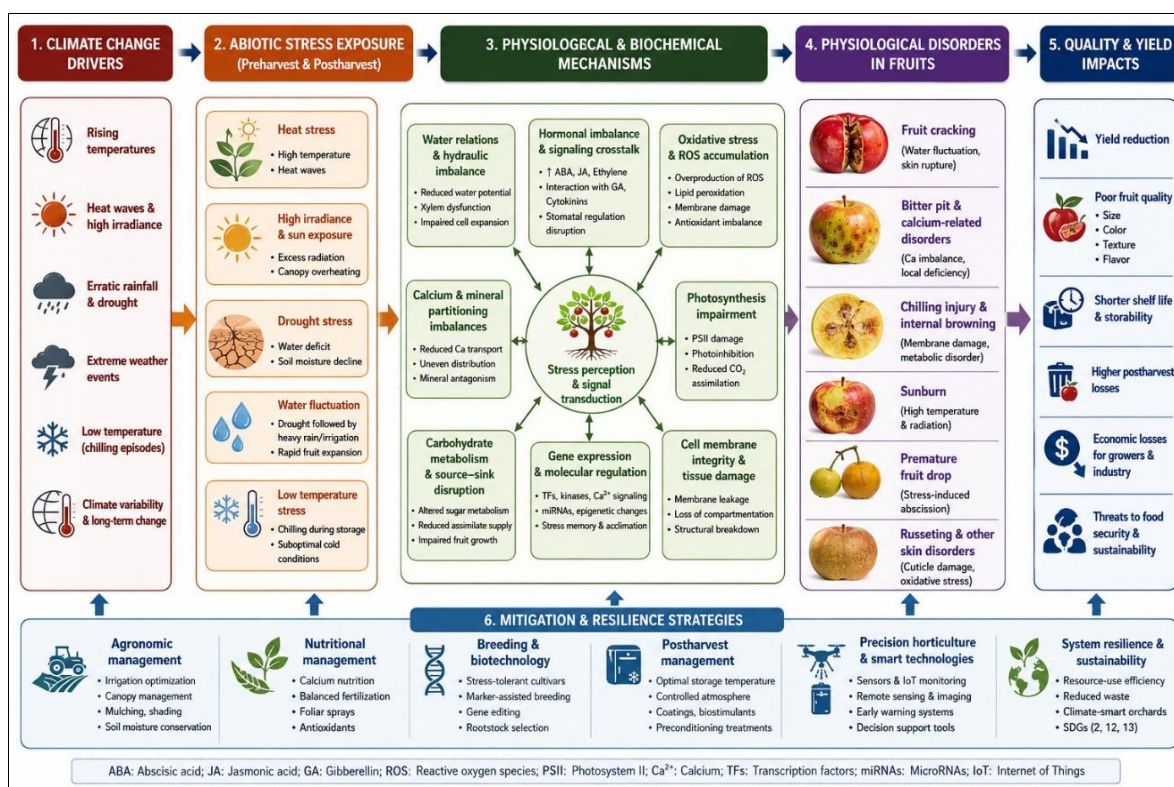


Fig 2: Climate change-physiological disorder mechanism pathway

Water Relations and Hydraulic Failure

Efficient water transport is essential for fruit growth, nutrient translocation, cell expansion, and calcium delivery. Fruit tissues rely on coordinated xylem and phloem transport systems to maintain hydration and metabolic activity throughout development. Under drought conditions, reduced soil water availability decreases xylem conductivity, limits transpiration-driven nutrient transport, and restricts cell expansion, resulting in reduced fruit growth and increased susceptibility to physiological disorders (Chaves *et al.*, 2010) [2].

Subsequent rehydration following drought can create rapid changes in fruit turgor pressure, leading to mechanical stress on epidermal tissues and increasing the risk of fruit cracking. Moreover, prolonged water deficits may alter hydraulic architecture, root functionality, and stress memory mechanisms in perennial fruit crops, thereby influencing susceptibility to physiological disorders across multiple growing seasons (Atkinson & Urwin, 2012; Osakabe *et al.*, 2014) [1, 19].

Hormonal Imbalance and Signaling Crosstalk

Plant hormones play central roles in coordinating responses to environmental stress. Among these, abscisic acid (ABA) serves as a primary regulator of drought adaptation by promoting stomatal closure, osmotic adjustment, and stress-responsive gene expression. However, under climate change-related stress scenarios, ABA signaling interacts extensively with other hormonal pathways, including ethylene, jasmonic acid, salicylic acid, gibberellins, cytokinins, and auxins (Verma *et al.*, 2016) [25].

Under combined heat and drought stress, complex hormonal crosstalk can alter reproductive development, carbon allocation, stomatal regulation, and stress tolerance. Such interactions often generate non-linear physiological responses that contribute to fruit abortion, premature fruit drop, reduced fruit size, and increased susceptibility to physiological disorders (Mittler, 2006; Zandalinas *et al.*, 2020) [17, 22].

Oxidative Stress and Membrane Damage

Reactive oxygen species are essential signaling molecules involved in plant stress perception and acclimation. However, excessive ROS production under severe environmental stress can overwhelm antioxidant defense systems and result in oxidative damage to cellular structures. Elevated ROS concentrations promote lipid peroxidation, protein oxidation, DNA damage, and membrane destabilization, ultimately impairing cellular function and fruit quality (Hasanuzzaman *et al.*, 2020) [8].

Oxidative stress has been repeatedly implicated in drought-induced physiological disorders, heat injury, sunburn, and chilling injury. In postharvest systems, membrane degradation caused by ROS accumulation is considered one of the principal mechanisms underlying chilling injury symptoms such as internal browning, pitting, mealiness, and tissue breakdown (Valenzuela *et al.*, 2017; Wang *et al.*, 1990) [24, 26].

Photosynthesis and Carbohydrate Metabolism

Photosynthesis is highly sensitive to environmental stress. Elevated temperatures, drought, and excessive irradiance reduce photosynthetic efficiency by impairing photosystem II activity, disrupting electron transport chains, increasing

photooxidative stress, and decreasing carbon assimilation rates (Hatfield & Prueger, 2015) [9].

Carbohydrates function not only as metabolic substrates but also as important signaling molecules involved in stress adaptation. Alterations in sugar metabolism can affect osmotic adjustment, antioxidant defense, reproductive success, and fruit development. Consequently, climate-induced disruption of source-sink relationships may contribute to poor fruit filling, internal tissue breakdown, reduced fruit size, premature fruit drop, and quality deterioration (Ruan, 2014; Zandalinas *et al.*, 2020) [21, 22].

Gene Expression and Emerging Molecular Regulation

Recent advances in molecular biology have revealed that fruit crop responses to abiotic stress are regulated through complex gene networks involving transcription factors, protein kinases, calcium-dependent signaling pathways, microRNAs, epigenetic modifications, and stress-memory mechanisms (Osakabe *et al.*, 2014) [19].

Particularly noteworthy is the growing application of transcriptomics, proteomics, metabolomics, and other multi-omics approaches to investigate physiological disorder development. In postharvest research, these technologies have improved understanding of the molecular mechanisms underlying chilling injury, internal browning, and fruit quality deterioration by linking changes in gene expression and metabolite profiles with visible physiological symptoms. Such approaches offer promising opportunities for identifying biomarkers and developing predictive tools for climate-resilient fruit production systems (Valenzuela *et al.*, 2017; Wang *et al.*, 2023) [24, 27].

Fruit Quality Effects

Climate change-induced physiological disorders affect not only fruit yield but also a wide range of quality attributes that determine consumer acceptance, storage potential, and market value. The economic consequences of these disorders are often more severe than yield losses because fruit quality directly influences grading standards, postharvest performance, and commercial profitability. Increasing evidence indicates that drought, heat stress, chilling stress, and compound stress events significantly alter fruit morphology, texture, color development, nutritional composition, flavor-related metabolites, and shelf life (Wang *et al.*, 2023; Zandalinas *et al.*, 2020) [27, 22].

Abiotic stresses frequently disrupt carbon assimilation and source-sink relationships, thereby reducing fruit growth and affecting the accumulation of sugars, organic acids, and secondary metabolites. Reduced photosynthetic activity under drought and heat stress limits carbohydrate availability for fruit development, resulting in smaller fruits, altered soluble solids concentration, impaired coloration, and reduced overall fruit quality (Chaves *et al.*, 2010; Ruan, 2014) [2, 21]. In addition, oxidative stress and membrane deterioration can negatively affect tissue firmness, juiciness, and storability by accelerating cellular senescence and metabolic dysfunction.

Postharvest physiological disorders further intensify quality losses. Chilling injury, for example, reduces consumer acceptance through symptoms such as mealiness, internal browning, pitting, peel discoloration, abnormal ripening, and accelerated deterioration following removal from cold storage. These changes not only shorten shelf life but also diminish nutritional and sensory quality, resulting in

substantial postharvest losses throughout the supply chain (Lurie & Crisosto, 2005; Wang *et al.*, 2023) ^[15, 27]. Consequently, the effects of climate-induced physiological disorders extend beyond orchard productivity and have important implications for food quality, market competitiveness, and economic sustainability.

Crop-Specific Perspectives

Apple

Apple (*Malus domestica* Borkh.) is one of the most extensively studied fruit crops with respect to climate-related physiological disorders, particularly bitter pit, superficial scald, internal browning, and other calcium-associated disorders. Research indicates that climatic conditions during fruit development strongly influence calcium transport, partitioning, and accumulation within fruit tissues. High temperatures, irregular water supply, vigorous vegetative growth, and drought stress can disrupt xylem-mediated calcium transport, thereby increasing susceptibility to bitter pit and related disorders (De Freitas & Mitcham, 2012; Kalcsits *et al.*, 2017) ^[3, 11].

Furthermore, climate variability can influence both preharvest physiological status and postharvest disorder expression. Consequently, effective management of physiological disorders in apple requires an integrated approach encompassing orchard nutrition, irrigation scheduling, crop load management, cultivar selection, and optimized storage practices (Kalcsits *et al.*, 2017) ^[11].

Citrus

Citrus species provide an important example of the effects of compound environmental stresses on fruit physiology. Unlike single-stress scenarios frequently studied under controlled conditions, commercial citrus orchards are often exposed simultaneously to drought, high temperature, and excessive solar radiation. Experimental studies have demonstrated that these combined stressors impair photosystem II activity, increase oxidative damage, disrupt redox homeostasis, and reduce photosynthetic efficiency more severely than individual stresses alone (Guidi *et al.*, 2019; Zandalinas *et al.*, 2020) ^[7, 22].

These physiological disturbances contribute to reduced fruit growth, impaired quality development, increased fruit drop, and greater susceptibility to environmental injury. Citrus therefore represents a valuable model for understanding how multiple climate-related stress factors interact to influence fruit crop performance under field conditions.

Peach and Nectarine

Peach (*Prunus persica*) and nectarine are widely recognized as model systems for studying chilling injury and postharvest physiological disorders. Although low-temperature storage is essential for extending shelf life and maintaining fruit quality, inappropriate storage temperatures or prolonged storage duration can induce mealiness, woolliness, internal browning, flesh breakdown, and texture deterioration (Lurie & Crisosto, 2005) ^[15].

The susceptibility of peach and nectarine fruits to chilling injury highlights the delicate balance between postharvest preservation and physiological stress. As global fruit trade increasingly relies on extended cold-chain logistics, understanding the mechanisms underlying chilling injury and developing effective mitigation strategies have become critical priorities for sustainable postharvest management.

Tropical and Subtropical Fruits

Tropical and subtropical fruits, including mango, banana, papaya, avocado, and several citrus species, are particularly vulnerable to chilling injury because they evolved under warm climatic conditions and possess limited tolerance to low-temperature storage. Expansion of international trade and long-distance transportation has increased reliance on refrigerated storage systems, thereby elevating the risk of chilling-related losses. Climate change may further exacerbate these challenges by increasing preharvest stress exposure, which can predispose fruit tissues to postharvest physiological disorders (Valenzuela *et al.*, 2017; Wang *et al.*, 2023) ^[24, 27].

Mineral Nutrition and Disorder Development

Mineral nutrition plays a central role in maintaining fruit structural integrity, physiological function, and resistance to abiotic stress. Among mineral nutrients, calcium has received the greatest attention because of its well-established association with numerous physiological disorders, including bitter pit, cork spot, internal breakdown, and storage-related disorders in pome fruits (De Freitas & Mitcham, 2012) ^[3].

However, contemporary research increasingly suggests that calcium deficiency alone does not fully explain disorder development. Recent studies indicate that susceptibility to bitter pit is influenced by multiple interacting factors, including genotype, rootstock characteristics, fruit growth rate, xylem functionality, transpiration dynamics, and the spatial distribution of calcium within fruit tissues (Kalcsits *et al.*, 2017) ^[11]. Consequently, physiological disorders should be viewed as the result of complex interactions among mineral nutrition, environmental stress, and developmental processes rather than simple nutrient deficiencies.

Climate change may intensify these interactions by altering transpiration rates, water relations, and fruit growth dynamics, thereby reducing calcium delivery to developing fruits even under adequate soil fertility conditions. Such findings highlight the importance of integrating nutritional management with irrigation, canopy management, and cultivar selection in climate-resilient fruit production systems.

Although calcium remains the most extensively studied mineral in relation to physiological disorders, other nutrients such as potassium, boron, magnesium, zinc, and silicon also contribute to fruit quality, membrane stability, stress tolerance, and tissue integrity. Nevertheless, compared with calcium-related disorders, mechanistic understanding of how these nutrients interact with climate-induced stress remains relatively limited. Addressing this knowledge gap represents an important research priority for developing comprehensive nutrient management strategies capable of reducing physiological disorder incidence under future climate scenarios.

Mitigation Strategies

Agronomic and Orchard-Level Approaches

Effective mitigation of climate change-induced physiological disorders begins with reducing plant exposure to hydraulic, thermal, and radiative stress. Orchard management practices that improve water availability, moderate canopy temperature, and enhance overall plant resilience are increasingly recognized as essential

components of climate-smart horticulture. Among these practices, precision irrigation, deficit irrigation scheduling, soil moisture monitoring, mulching, and improved water-use efficiency have demonstrated considerable potential for reducing drought-related physiological stress while maintaining fruit yield and quality (Chaves *et al.*, 2010; Flexas *et al.*, 2010) [2, 5].

Canopy architecture and orchard microclimate management also play critical roles in mitigating heat and radiation stress. Techniques such as reflective mulches, shade nets, evaporative cooling systems, kaolin particle films, and optimized pruning can reduce fruit surface temperature, limit photoinhibition, and decrease the incidence of sunburn and heat-related disorders (Glenn *et al.*, 2002) [6]. Because climate-induced physiological disorders often arise from interactions among multiple environmental stressors, integrated orchard management approaches are generally more effective than single interventions.

Nutritional and Biochemical Interventions

Nutritional management remains one of the most widely adopted strategies for reducing physiological disorder incidence in fruit crops. Calcium-based spray programs are routinely employed to minimize bitter pit, cork spot, and related calcium-deficiency disorders. However, contemporary evidence suggests that calcium applications should not be viewed as standalone solutions. Their effectiveness depends on interactions with cultivar genetics, rootstock characteristics, irrigation management, crop load regulation, and fruit growth dynamics (De Freitas & Mitcham, 2012; Kalcsits *et al.*, 2017) [3, 11].

In postharvest systems, several biochemical treatments have shown promise in alleviating chilling injury and preserving fruit quality. Applications of methyl jasmonate, salicylic acid, glycine betaine, nitric oxide donors, edible coatings, and antioxidant-based formulations have been reported to enhance membrane stability, improve antioxidant defense systems, and reduce oxidative damage during cold storage (Valenzuela *et al.*, 2017; Wang *et al.*, 2023) [24, 27]. Likewise, preconditioning treatments involving controlled temperature exposure, intermittent warming, and light-based technologies have demonstrated beneficial effects in reducing chilling-related physiological damage.

Breeding and Biotechnology

Long-term adaptation to climate change will require the development of fruit cultivars with enhanced tolerance to drought, heat stress, mineral imbalances, and postharvest physiological disorders. Conventional breeding programs increasingly incorporate physiological and molecular traits associated with stress tolerance, including improved water-use efficiency, antioxidant capacity, osmotic adjustment, and nutrient-use efficiency (Atkinson & Urwin, 2012) [1].

Advances in genomics, transcriptomics, genome-wide association studies (GWAS), marker-assisted selection, and gene-editing technologies are providing new opportunities to accelerate the development of climate-resilient fruit cultivars. Research has identified numerous transcription factors, stress-responsive genes, calcium-signaling components, and regulatory pathways involved in abiotic stress adaptation. Nevertheless, translating molecular discoveries into commercially successful cultivars remains challenging because stress tolerance is typically governed by complex polygenic interactions that are strongly

influenced by environmental conditions (Osakabe *et al.*, 2014; Zandalinas *et al.*, 2020) [19, 22].

Precision Horticulture and Smart Technologies

Precision horticulture represents one of the most promising approaches for proactive management of climate-induced physiological disorders. Advances in sensor technology, remote sensing, thermal imaging, artificial intelligence (AI), machine learning, unmanned aerial vehicles (UAVs), and Internet of Things (IoT)-based monitoring systems are enabling real-time assessment of orchard conditions and plant physiological status (Zhang *et al.*, 2014) [28].

Although direct applications of AI for physiological disorder prediction remain limited, emerging evidence suggests that integration of environmental monitoring, plant physiological indicators, and predictive analytics can substantially improve early detection and risk assessment. Thermal imaging can identify canopy heat stress before visible symptoms appear, while hyperspectral imaging and molecular biomarkers offer opportunities for detecting physiological imbalances associated with nutrient deficiencies, chilling injury, and water stress (Mahlein, 2016; Zhang *et al.*, 2014) [16, 28].

From a practical perspective, precision horticulture can be viewed as the operational extension of plant stress physiology, enabling growers to make timely decisions regarding irrigation scheduling, canopy management, harvest timing, storage conditions, and postharvest treatments before irreversible physiological damage occurs.

Sustainability and Climate Resilience

Reducing the incidence of physiological disorders contributes directly to the sustainability of fruit production systems. Improved management of climate-related disorders enhances resource-use efficiency, reduces postharvest losses, improves fruit quality, and stabilizes economic returns for growers. Given the high resource inputs associated with fruit production, minimizing physiological losses represents an important strategy for improving environmental and economic sustainability (FAO, 2023) [4]. Climate-resilient fruit production systems simultaneously support environmental objectives such as water conservation and efficient resource utilization, economic objectives such as yield stability and reduced postharvest losses, and social objectives related to food security, farmer livelihoods, and supply-chain resilience. Consequently, management of physiological disorders contributes directly to the achievement of several United Nations Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), and SDG.

Challenges and Limitations

Despite substantial advances in understanding fruit physiological disorders, significant challenges remain. One of the primary difficulties is the multifactorial nature of these disorders. Many disorders develop through complex interactions among environmental conditions, genetic factors, mineral nutrition, physiological status, and postharvest management practices. Consequently, simple cause-and-effect relationships are often insufficient to explain disorder occurrence and severity.

For example, bitter pit cannot be attributed solely to calcium deficiency, while chilling injury results from interconnected

disturbances involving membrane integrity, oxidative metabolism, hormonal regulation, and energy balance. Such complexity complicates diagnosis, prediction, and management under commercial production conditions (De Freitas & Mitcham, 2012; Kalcsits *et al.*, 2017) [3, 11].

Another major limitation is the disconnect between controlled-environment studies and real-world orchard conditions. Although laboratory and greenhouse experiments provide valuable mechanistic insights, orchard environments expose fruit crops to multiple interacting stressors that vary spatially and temporally. Bridging this gap requires multidisciplinary approaches that integrate molecular biology, plant physiology, agronomy, postharvest science, and precision agriculture technologies (Mittler, 2006; Zandalinas *et al.*, 2020) [17, 22].

Research Gaps and Future Directions

Several critical research priorities must be addressed to improve understanding and management of climate change-induced physiological disorders in fruit crops.

First, long-term field-based studies are needed to determine how recurring heat waves, drought cycles, irregular precipitation patterns, and compound stress events influence disorder development across multiple growing seasons in perennial fruit systems. Such studies are essential for understanding cumulative stress effects and stress-memory responses under realistic production conditions (Atkinson & Urwin, 2012) [1].

Second, research efforts should expand beyond relatively well-studied disorders such as apple bitter pit and chilling injury in temperate fruits. Greater attention is needed for tropical and subtropical fruit crops, emerging physiological disorders, and mixed-stress scenarios that better reflect future climate conditions.

Third, advances in transcriptomics, proteomics, metabolomics, ionomics, and phenomics should be integrated with physiological and agronomic research to

identify reliable biomarkers of disorder susceptibility and stress resilience. Although omics technologies have generated substantial mechanistic knowledge, their practical application in commercial orchard management remains limited (Osakabe *et al.*, 2014; Wang *et al.*, 2023) [19, 27].

Finally, precision horticulture technologies require rigorous validation under commercial conditions. Future research should focus on developing robust disorder forecasting systems that combine thermal sensing, hyperspectral imaging, environmental monitoring, machine learning, and physiological indicators to support evidence-based decision-making and early intervention strategies.

Conceptual Framework

Climate change-induced physiological disorders can be conceptualized as a cascading sequence of interconnected events. Climate change increases exposure to abiotic stressors such as drought, heat, erratic rainfall, excessive radiation, and chilling stress. These environmental pressures disrupt water relations, hormonal regulation, mineral transport, photosynthesis, carbohydrate metabolism, and redox homeostasis. The resulting physiological imbalances trigger the development of disorders such as fruit cracking, bitter pit, sunburn, chilling injury, internal browning, and premature fruit drop.

These disorders subsequently reduce fruit yield, storage life, market quality, and economic returns. However, the implementation of integrated mitigation strategies—including climate-smart orchard management, optimized nutrition, genetic improvement, postharvest interventions, and precision monitoring technologies—can substantially enhance system resilience and reduce climate-related losses. This framework emphasizes that physiological disorders should be viewed not as isolated symptoms but as emergent outcomes of complex interactions among environmental stress, plant physiology, and management practices within fruit production systems.

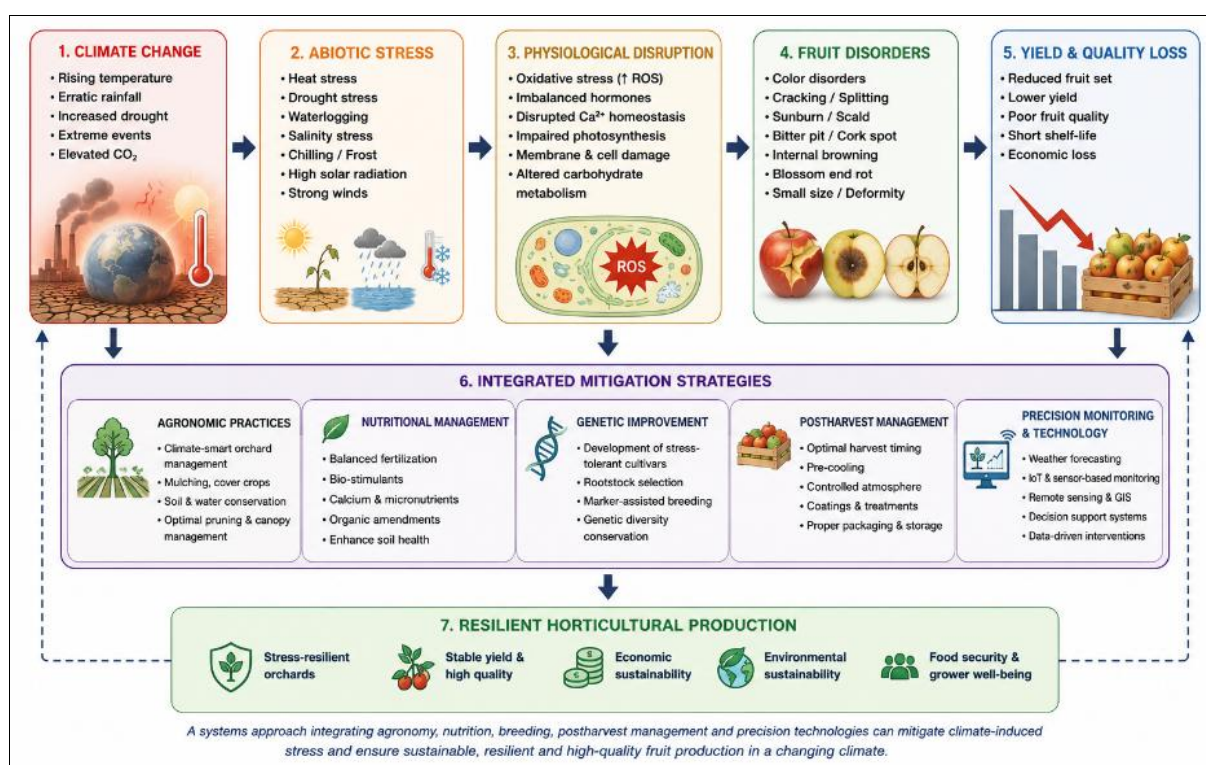


Fig 3: Conceptual framework for climate-resilient fruit production

Conclusion

Climate change is significantly increasing the incidence and severity of physiological disorders in fruit crops through rising temperatures, drought, erratic rainfall, excessive solar radiation, and chilling-related stresses. These environmental factors disrupt key physiological processes, including water relations, calcium transport, hormonal regulation, photosynthesis, carbohydrate metabolism, membrane integrity, and redox homeostasis, leading to disorders such as fruit cracking, bitter pit, chilling injury, sunburn, and internal browning. Current evidence indicates that these disorders result from complex interactions among climatic conditions, plant physiology, mineral nutrition, genotype, and management practices rather than from single causal factors. Therefore, effective mitigation requires integrated approaches combining climate-smart orchard management, precision irrigation, balanced nutrition, improved postharvest technologies, stress-tolerant cultivars, and precision horticultural tools. Future research should focus on understanding compound stress effects, validating mitigation strategies under field conditions, and integrating omics-based discoveries with predictive monitoring systems to enhance the resilience and sustainability of fruit production under changing climatic conditions.

References

- Atkinson CJ, Urwin PE. The interaction of plant biotic and abiotic stresses: From genes to the field. *Journal of Experimental Botany*. 2012;63(10):3523-3543.
- Chaves MM, Flexas J, Pinheiro C. Photosynthesis under drought and salt stress: Regulation mechanisms from whole plant to cell. *Annals of Botany*. 2010;103(4):551-560.
- De Freitas ST, Mitcham EI. Factors involved in fruit calcium deficiency disorders. *Horticultural Reviews*. 2012;40(1):107-146.
- Food and Agriculture Organization of the United Nations. *The State of Food and Agriculture 2023*. Rome: FAO; 2023.
- Flexas J, Galmés J, Gallé A, Gulías J, Pou A, Ribas-Carbó M, *et al.* Improving water use efficiency in grapevines: Potential physiological targets for biotechnological improvement. *Australian Journal of Grape and Wine Research*. 2010;16:106-121.
- Glenn DM, Prado E, Erez A, McFerson J, Puterka GJ. A reflective processed-kaolin particle film affects fruit temperature, radiation reflection, and solar injury in apple. *Journal of the American Society for Horticultural Science*. 2002;127(2):188-193.
- Guidi L, Lo Piccolo E, Landi M. Chlorophyll fluorescence, photoinhibition and abiotic stress: does it make any difference the fact to be a C₃ or C₄ species? *Frontiers in Plant Science*. 2019;10:174.
- Hasanuzzaman M, Bhuyan MB, Zulfiqar F, Raza A, Mohsin SM, Mahmud JA, *et al.* Reactive oxygen species and antioxidant defense in plants under abiotic stress: Revisiting the crucial role of a universal defense regulator. *Antioxidants*. 2020;9(8):681.
- Hatfield JL, Prueger JH. Temperature extremes: Effect on plant growth and development. *Weather and Climate Extremes*. 2015;10:4-10.
- Intergovernmental Panel on Climate Change. *Climate Change 2023: Synthesis Report*. Geneva: IPCC; 2023.
- Kalsits L, van der Heijden G, Reid M, Mullin K. Calcium Absorption during Fruit Development in ‘Honeycrisp’ Apple Measured Using ⁴⁴Ca as a Stable Isotope Tracer. *HortScience*. 2017;52(12):1804-1809.
- Knoche M, Lang A. Ongoing growth challenges fruit skin integrity. *Critical Reviews in Plant Sciences*. 2017;36(3):190-215.
- Knoche M, Khanal BP, Brüggewirth M, Thapa S. Patterns of microcracking in apple fruit skin reflect those of the cuticular ridges and of the epidermal cell walls. *Planta*. 2018;248(2):293-306.
- Lesk C, Rowhani P, Ramankutty N. Influence of extreme weather disasters on global crop production. *Nature*. 2016;529(7584):84-87.
- Lurie S, Crisosto CH. Chilling injury in peach and nectarine. *Postharvest Biology and Technology*. 2005;37(3):195-208.
- Mahlein AK. Plant disease detection by imaging sensors-parallels and specific demands for precision agriculture and plant phenotyping. *Plant Disease*. 2016;100(2):241-251.
- Mittler R. Abiotic stress, the field environment and stress combination. *Trends in Plant Science*. 2006;11(1):15-19.
- Moretti CA, Mattos LM, Calbo AG, Sargent SA. Climate changes and potential impacts on postharvest quality of fruit and vegetable crops: A review. *Food Research International*. 2010;43(7):1824-1832.
- Osakabe Y, Osakabe K, Shinozaki K, Tran LSP. Response of plants to water stress. *Frontiers in Plant Science*. 2014;5:86.
- Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, *et al.* The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ*. 2021;372:n71.
- Ruan YL. Sucrose metabolism: gateway to diverse carbon use and sugar signaling. *Annual Review of Plant Biology*. 2014;65:33-67.
- Zandalinas SI, Fichman Y, Devireddy AR, Sengupta S, Azad RK, Mittler R. Systemic signaling during abiotic stress combination in plants. *Proceedings of the National Academy of Sciences of the United States of America*. 2020;117(24):13810-13820. <https://doi.org/10.1073/pnas.2005077117>
- Schrader LE, Zhang J, Duplaga WK. Two types of sunburn in apple caused by high fruit surface (peel) temperature. *Plant Health Progress*. 2001;2(1):3.
- Valenzuela JL, Manzano S, Palma F, Carvajal F, Garrido D, Jamilena M. Oxidative stress associated with chilling injury in immature fruit: postharvest technological and biotechnological solutions. *International Journal of Molecular Sciences*. 2017;18(7):1467.
- Verma V, Ravindran P, Kumar PP. Plant hormone-mediated regulation of stress responses. *BMC Plant Biology*. 2016;16(1):86.
- Wang CY. *Chilling injury of horticultural crops*. Boca Raton: CRC Press; 1990.
- Wang GL, Wu JQ, Chen YY, Xu YJ, Zhou CL, Hu ZZ, *et al.* More or less: recent advances in lignin accumulation and regulation in horticultural crops. *Agronomy*. 2023;13(11):2819.
- Zhang C, Walters D, Kovacs JM. Applications of low altitude remote sensing in agriculture upon farmers' requests-a case study in northeastern Ontario, Canada. *PLoS ONE*. 2014;9(11):e112894.