The impact of global warming on fruit crops and mitigation strategies: A comprehensive review

El impacto del calentamiento global en los cultivos de frutales y las estrategias de mitigación: una revisión comprensiva

Ali İkinci[1*]

ABSTRACT

Global warming poses a significant challenge to the agricultural sector, with fruit cultivation being particularly susceptible due to its intricate relationship with specific climatic conditions. The observed increases in global air temperatures, coupled with alterations in precipitation patterns and a higher frequency of extreme weather events, are fundamentally reshaping fruit production on a worldwide scale. This article explores the multifaceted impacts of global warming on fruit cultivation, highlighting key issues such as shifts in phenological phases, declines in crop yields, increased pressure from pests and diseases, and the growing scarcity of water resources. Furthermore, it provides a comprehensive analysis of adaptation and mitigation strategies, encompassing sustainable agricultural practices, the development of climate-resilient fruit varieties, and the implementation of effective water management strategies. Addressing these complex challenges is of paramount importance to ensure the long-term viability and economic sustainability of fruit production in the face of evolving climatic conditions.

Key words: climate adaptation, phenological stages, yield losses, adaptation strategies.

RESUMEN

El calentamiento global plantea un desafío significativo para el sector agrícola, siendo el cultivo de frutales particularmente susceptible debido a su intrincada relación con condiciones climáticas específicas. Los aumentos observados en las temperaturas globales del aire, junto con las alteraciones en los patrones de precipitación y una mayor frecuencia de eventos climáticos extremos, están reconfigurando fundamentalmente la producción de frutales a escala global. Este artículo profundiza en los impactos multifacéticos del calentamiento global en el cultivo de frutales, explorando cuestiones críticas como los cambios en las fases fenológicas, la disminución de los rendimientos de los cultivos, la mayor presión de plagas y enfermedades, y la creciente escasez de recursos hídricos. Además, proporciona un análisis comprensivo de las estrategias de adaptación y mitigación, que abarcan las prácticas agrícolas sostenibles, el desarrollo de variedades de frutales resistentes al clima y la implementación de estrategias efectivas de gestión del agua. Abordar estos desafíos complejos es de suma importancia para asegurar la viabilidad a largo plazo y la sostenibilidad económica de la producción de frutales bajo las condiciones climáticas en evolución.

Palabras clave: adaptación al clima, fases fenológicas, pérdidas de rendimiento, estrategias de adaptación.

Introduction

Climate change is recognized as one of the most critical global-scale issues of the 21st century, exerting profound and widespread impacts on the agricultural sector (IPCC, 2021). The persistently rising global temperatures, coupled with unpredictable and variable weather conditions and an increasing frequency of extreme climatic events, significantly affect agricultural production, particularly fruit cultivation (Fischer *et al*., 2016). Fruit crops, due to their high sensitivity to specific climatic requirements, are highly vulnerable to these environmental changes (Ameen *et al*., 2023; Osorio-Marín *et al*., 2024) that adversely affect their growth cycles, overall yields, and final product quality.

The importance of thoroughly investigating and understanding the effects of climate change on fruit cultivation extends beyond the boundaries of mere food production. Fruits are recognized as an indispensable and fundamental component of the human diet, providing a range of vital nutrients such as vitamins, minerals, fiber, and antioxidants that are essential for human health (Ameen *et al*., 2023). The economic dimension of fruit production also holds a significant place on a global scale. This sector not only

Received for publication: February 13, 2025. Accepted for publication: May 10, 2025.

Doi: 10.15446/agron.colomb.v43n2.118860

[1] Department of Horticulture, Faculty of Agriculture, Harran University, Şanlıurfa (Türkiye).
[*] Corresponding author: aliikinci@harran.edu.tr

constitutes the livelihood for millions of farmers worldwide but also makes substantial contributions to international trade, forming a critical pillar of both local and global economies (Raju *et al*., 2024). Therefore, given the systemic threats posed by a shifting climate, a deep understanding of how these changes affect fruit cultivation has become a vital necessity (Osorio-Marín *et al*., 2024; Yadav *et al*., 2023). This understanding is crucial to develop effective adaptation strategies aimed at sustainably maintaining production levels, ensuring global food security, and preserving the vitality of rural economies in a changing world (Karagatiya *et al*., 2023).

The primary objective of this article is to comprehensively address the multifaceted impacts of global warming on fruit cultivation. In this context, issues such as changes occurring in phenological processes (*e.g.*, flowering timing and fruit ripening) (Fujisawa & Kobayashi, 2010; Funes *et al*., 2016), reductions in crop yields (*e.g.*, fruit size and number) (Challinor *et al*., 2014), declines in fruit quality (*e.g.*, sugar content and acidity) (Fujisawa & Kobayashi, 2010), and the increased susceptibility of plants to pests and diseases (*e.g.*, the emergence of new pest species) (Jones *et al*., 2012; Moinina *et al*., 2019) will be examined. Furthermore, adaptation strategies such as the adoption of sustainable agricultural practices, the modernization of irrigation techniques, and genetic improvement studies will also be discussed to provide applicable solutions to minimize climate-induced risks and make fruit cultivation more resilient to the adverse effects of climate change.

Climate change, with its primary drivers being temperature increase and altered precipitation patterns, has become one of the most significant sources of global concern in recent years (Fischer *et al*., 2016; IPCC, 2021). Horticultural products, exhibiting a high degree of sensitivity to climatic conditions, are significantly affected by this change, which brings about significant challenges in this vital area of product production (Ameen *et al*., 2023; Osorio-Marín *et al*., 2024). Climate modeling studies predict that horticultural products are highly susceptible to the potential impacts of climate change, which could result in significant adverse effects (Karagatiya *et al*., 2023; Yadav *et al*., 2023). As both the frequency and severity of extreme weather events, such as tropical storms, hurricanes, and typhoons, are progressively increasing (Osorio-Marín *et al*., 2024), the necessity and importance of being prepared for such events is becoming even more pronounced. Although researchers have a comprehensive understanding of the potential risks that climate change may pose in the future, thanks to significant advances in computer technologies, policymakers and planners have not yet taken sufficient steps towards effective actions to mitigate the potential damage that may arise in different sectors of agriculture (Fischer *et al*., 2016; IPCC, 2021; Karagatiya *et al*., 2023).

Fruit bearing plants are particularly vulnerable to the significant changes expected and projected in the climate due to their need for high chilling requirements to terminate the dormancy process (Luedeling, 2012; Luedeling *et al*., 2011). Most fruit species from temperate regions need to be exposed to low temperatures for a certain period to eliminate physical and/or physiological dormancy (Luedeling *et al*., 2011; Rodríguez *et al*., 2021). This chilling period is critical for the regular opening of buds, the timely onset of flowering, and ultimately, the realization of fruit formation (Luedeling *et al*., 2011; Rodríguez *et al*., 2021). However, changing climatic conditions are expected to lead to significant changes in chilling hours and heat hour accumulation, which pose new and complex challenges for the fruit industry (Noorazar *et al*., 2022; Osorio-Marín *et al*., 2024; Ramírez & Kallarackal, 2015). Fruit trees, which are perennial plants, will be exposed to stress factors caused by changing climatic conditions for many years, unlike annual plants, where the effects of extreme weather events are limited to a single crop growing season. These long-term effects of climate change on perennial fruit plants have not yet been sufficiently studied in the scientific literature. This article aims to comprehensively examine the effects of climate change on the different stages of fruit cultivation. In this context, all stages, from chilling requirements to flowering, fruit set, fruit development, and postharvest processes, including changes in secondary metabolites, phytochemicals, and fruit nutritional value, will be discussed. In addition, adaptation recommendations in the form of various cultural practices are presented to overcome these unprecedented challenges and make fruit cultivation more resilient to climate change.

Effects of global warming on fruit cultivation

Global warming is projected to have complex and far-reaching effects on fruit cultivation. These effects can manifest themselves in a wide range, from the physiological processes of products to the dynamics of harmful organisms, from the availability of water resources to the geographical distribution of orchards.

Direct effects

Temperature effects

High temperature stress: Excessively high temperatures can negatively affect essential physiological processes in fruit crops, such as photosynthesis (Flórez-Velasco *et al*., 2024), respiration, and enzyme activities (Ameen *et al*., 2023; Osorio-Marín *et al*., 2024). Photosynthetic activity significantly decreases under high temperature stress, which limits the plant capacity to produce sugars that are vital for fruit development (Ameen *et al*., 2023; Yadav *et al*., 2023). High temperatures can also reduce pollen viability and fruit set rates (Ameen *et al*., 2023). The severity of temperature stress can vary greatly among fruit species and even among different varieties of the same species. For example, some apple varieties are more susceptible to heat-induced fruit drop than others, while some stone fruits, such as cherries and plums, may produce smaller and lower quality fruits under high temperature stress (Ameen *et al*., 2023; Osorio-Marín *et al*., 2024).

A less apparent but critical impact on plant physiology, particularly prevalent in fruit crops, is night-time heat stress. Elevated nocturnal temperatures increase plant respiration rates, leading to the consumption of a significant portion of carbohydrates (sugars) produced during daytime photosynthesis. This limits the net energy available for plant growth and fruit development. In apples, elevated night temperatures have been shown to suppress anthocyanin biosynthesis by down-regulating key genes (*e.g., MdCHS*, *MdF3H*, *MdDFR*, *MdANS*, and *MdUFGT*), resulting in reduced red pigmentation and diminished visual quality (Ryu *et al*., 2017). In peaches, recent studies demonstrated that elevated day/night temperatures, such as 30°C/22 °C, significantly impair red flesh coloration and overall fruit quality, including reductions in fruit firmness, contents of soluble solids, and titratable acidity (Jayasooriya *et al*., 2025). Physiologically, night-time heat stress may also lead to chlorophyll degradation, reduced photosynthetic efficiency, and hormonal imbalance during critical phases such as flowering and fruit set. Agronomically, it adversely affects fruit size, color, firmness, and flavor, leading to both yield and quality losses. Therefore, understanding the physiological mechanisms and agronomic consequences of night-time heat stress is a crucial component of climate change adaptation strategies (Ameen *et al*., 2023; Yadav *et al*., 2023).

Changes in chilling requirements: Many temperate fruit species, such as apples, pears, cherries, peaches, and plums, require a specific period of chilling hours (generally below 7°C) during the winter season (Ameen *et al*., 2023; Yadav *et al*., 2023). This chilling process is necessary for the plants to break dormancy and initiate regular and adequate flowering in the spring (Ramírez & Kallarackal, 2015; Rodríguez *et al*., 2021). However, increasingly warmer winters can lead to a decrease in the accumulation of chilling hours required by the plants (Luedeling *et al*., 2011; Ramírez & Kallarackal, 2015; Rodríguez *et al*., 2021). This can cause untimely or insufficient bud break, irregular flowering, and consequently, lower fruit set rates and yield (Noorazar *et al*., 2022; Salama *et al*., 2021). This change in chilling hour requirements can lead to significant yield losses in fruit production. Chilling hour requirements between different fruit species and varieties can vary significantly (Noorazar *et al*., 2022; Rodríguez *et al*., 2021; Salama *et al*., 2021).

Deviations in phenological stages: Rising global temperatures can cause phenological stages, such as flowering and bud break, to begin earlier and also result in their shorter duration in fruit trees (El Yaacoubi *et al*., 2014; Fu *et al*., 2022). This early onset can make fruit trees more vulnerable to late spring frosts, especially after mild winters followed by sudden cold snaps. Such changes in the timing and duration of phenological stages can disrupt the critical synchronization between fruit flowering and the activity of natural pollinators, negatively affecting fruit set (Fu *et al*., 2022). In addition, increased temperatures can accelerate fruit development, thereby shortening the fruit filling period and reducing the time available for optimal sugar accumulation, which may ultimately diminish both yield and fruit quality (Jayasooriya *et al*., 2025).

Water resources

Drought: The increasing frequency and severity of drought events can lead to severe water stress in fruit trees (Kumar *et al*., 2019). From a physiological standpoint, water deficit disrupts stomatal conductance and reduces photosynthetic rates, leading to impaired carbon assimilation and limited biomass accumulation. It can also alter hormonal balances (*e.g.*, increased abscisic acid content), reduce cell expansion, and accelerate leaf senescence, ultimately limiting vegetative growth and reproductive success (Fischer *et al*., 2016). These physiological constraints can slow down tree growth, reduce fruit size, decrease overall yield, and negatively affect fruit quality parameters such as texture, juiciness, and sugar content (Kumar *et al*., 2019).

However, mild to moderate drought stress during specific stages of fruit development has been reported to promote the accumulation of sugars, anthocyanins, and other antioxidants in some species, potentially enhancing certain quality attributes such as fruit flavor and skin coloration (Jayasooriya *et al*., 2025; Silva *et al*., 2018). This duality underscores the complexity of drought responses in fruit crops. Drought stress can also compromise tree health by weakening structural defenses and metabolic resilience, thereby increasing vulnerability to insect pests and diseases (Kumar *et al*., 2019).

The magnitude of drought effects on fruit production varies significantly depending on the species, cultivar, developmental stage, and stress duration, with some fruit species (olive, fig, or pomegranate) exhibiting greater drought tolerance than others (Silva *et al*., 2018). Regions already prone to water scarcity, such as California, the Mediterranean basin, and parts of Australia, are especially at risk of long-term production losses due to these adverse impacts (El Jaouhari *et al*., 2018; Nath *et al*., 2018).

Flooding: More frequent occurrences of excessive rainfall and flooding can damage fruit crops. Especially in soils with insufficient drainage, problems such as excessive water accumulation and root rot can occur (Malhotra *et al*., 2017). From a physiological perspective, prolonged soil saturation creates hypoxic to anoxic conditions in the root zone, impairing root respiration, nutrient and water uptake, and triggering oxidative stress. Energy production shifts from aerobic to less-efficient anaerobic pathways, leading to toxic metabolite accumulation (ethanol, reactive oxygen species), decreased fine root growth, and compromised root integrity (McGee *et al*., 2022; Wurms *et al*., 2023).

These disruptions translate agronomically into reduced carbohydrate translocation, impaired photosynthesis, and hormonal imbalance—impacting flowering, fruit set, and growth duration. In peach trees, flooding has been shown to alter carbohydrate and nitrogen metabolism, increasing leaf sugar concentrations while simultaneously inhibiting nitrate assimilation and glycolytic enzyme activities, which ultimately impairs fruit filling and reduces fruit size and yield (McGee *et al*., 2022). Routine operations in orchards may also be disrupted, and long-term infrastructure damage can compound crop losses (Kourgialas & Karatzas, 2016; Malhotra *et al*., 2017).

Evapotranspiration: Rising temperatures directly increase evapotranspiration rates that can further exacerbate water scarcity even if rainfall patterns remain relatively constant. This increase in evapotranspiration creates an additional stress load on fruit trees, increasing irrigation needs (Zhang *et al*., 2013).

Extreme weather events

Heat waves, frost events, hail, and severe winds: Extreme weather events can cause direct physical damage to fruit trees, the flowers, and developing fruits. For example, heat waves can lead to sunburn and desiccation of fruits (Van Asten *et al*., 2011), while late spring frosts can completely destroy newly formed buds and flowers. Hail can damage the outer skins of fruits, reducing their market value (Bal *et al*., 2014) and increasing their susceptibility to rot. Severe winds can cause premature fruit drop, leading to significant yield losses (Chawla *et al*., 2011; Veste *et al*., 2020).

Indirect effects

Pests and diseases

Expansion of pest distribution areas: Rising global temperatures can expand the geographic distribution areas of some insect species that are considered pests (Sharma, 2014). This allows them to settle in regions where they could not previously survive due to the temperature factor. As a result, new pest species that have not been seen before may emerge in fruit-growing regions, which increases the complexity of pest management strategies (Moinina *et al*., 2019). Changes in rainfall patterns can also affect the life cycles of pests. For example, pest pressure may increase in some regions while decreasing in others (Moinina *et al*., 2019; Sharma, 2014).

Increased prevalence of diseases: Changes in temperature and humidity conditions can create more suitable microclimates for the development and spread of fungal and bacterial diseases affecting fruit trees (Jones *et al*., 2012; Yáñez-López *et al*., 2012). Rising temperatures can extend the active growing season of some pathogens, while increased humidity can promote the development of fungal diseases (Ghini, 2011). For example, in some fruit species such as strawberries, the frequency of fungal diseases can significantly increase in hot and humid climatic conditions (Yáñez-López *et al*., 2012).

Pest and disease interactions: Fruit trees that are weakened by factors such as high temperature or water stress become more vulnerable to both insect pest attacks and various diseases. For example, a tree that is already under stress due to drought may lose its normal resistance to fungal pathogens (Nawaz *et al*., 2020). This can trigger a chain reaction in which the primary stress factor increases the tree's overall vulnerability to other stress factors.

Disruptions in the pollination process

Disruptions in pollinator activity: The increase in global temperatures can disrupt the delicate balance between the flowering time of fruit trees and the activities of pollinators (especially bees), which play a critical role in the pollination of these trees (Forrest, 2015). Temperature changes can affect both the flowering time and the emergence time of pollinators, leading to a mismatch that negatively affects pollination success (Forrest, 2015; Millard *et al*., 2023). Changes in the behavior of pollinators, such as deviations in their foraging habits due to changing flower resources, can further negatively affect the pollination process (Millard *et al*., 2023; Scaven & Rafferty, 2013).

Deterioration of soil health

Soil erosion: The increase in the frequency and intensity of rainfall events, combined with the decrease in vegetation cover in some areas, such as due to drought-related plant deaths, can significantly increase soil erosion, especially in sloping lands or orchards with poor vegetation cover (Li & Fang, 2016). In some vulnerable regions, projected climate scenarios suggest that soil erosion rates could increase by 17% to 58% by the end of the 21st century under high-emission scenarios (Li & Fang, 2016). Soil erosion leads to the loss of the top fertile layer of the soil. This layer is rich in organic matter and nutrients necessary for plants, which leads to a decrease in soil fertility and water holding capacity (Kaye & Quemada, 2017).

Loss of soil organic matter and nutrients: Changes in temperature and humidity regimes can deeply affect the soil's organic matter content and nutrient cycling. High temperatures can increase the decomposition rate of organic matter, reducing the overall fertility of the soil (Sierra *et al*., 2015). Changes in rainfall patterns can affect the leaching of nutrients in the soil and their availability to plants. Drought conditions can also suppress the activities of microorganisms living in the soil, further negatively affecting nutrient cycling (Scavo *et al*., 2022).

Regional differences

The effects of global warming on fruit cultivation show significant differences between geographical regions. These differences stem from factors such as the region's basic climatic characteristics, its topographic structure, current agricultural techniques, and the diversity of fruit species grown (Del Pozo *et al*., 2019; Raju *et al*., 2024).

Mediterranean region: The Mediterranean climate zone is a critical region where important fruit products such as olives, grapes, citrus fruits, and stone fruits are grown. However, this region is expected to face an increased risk of drought in the future, experience more frequent and severe heat waves, and experience significant decreases in chilling hours (Del Pozo *et al*., 2019). These climate changes can lead to yield declines in fruit production in the region, changes in fruit quality, and geographical shifts in suitable areas for fruit cultivation (Del Pozo *et al*., 2019).

California (USA): California is an important region for the cultivation of high-value fruit products (including almonds, citrus fruits, grapes, and stone fruits) (Pathak *et al*., 2018). However, prolonged droughts and an increase in the frequency and intensity of heat waves pose serious challenges for fruit cultivation in this region. The decrease in snow cover in the Sierra Nevada mountains, which is the main source of irrigation water, also raises concerns about the sustainability of water resources (Pathak *et al*., 2018).

Tropical regions: Regions where tropical fruits such as mangoes, bananas, papayas, and pineapples are grown are adversely affected by changes in rainfall patterns, increases in both drought and flood risks, and the intensification of pest and disease pressure. These regions are also expected to experience an increase in the frequency and severity of extreme weather events (Lauri *et al*., 2013; Nath *et al*., 2018). In tropical highland areas, such as the Andes, fruit crops are additionally affected by altitude-dependent temperature shifts, which can alter photosynthetic efficiency and fruit development patterns (Flórez-Velasco *et al*., 2024).

Australia: In Australia, the decrease in winter cold has already begun to negatively affect apple production in some regions (Darbyshire *et al*., 2013). Other fruit species are experiencing yield losses due to more frequent and severe heat events. The state of water resources, especially the increasing risk of drought, is a major concern for Australian fruit cultivation (Head *et al*., 2014).

South Africa: South Africa is an important region for the production of grapes, citrus fruits, and stone fruits. However, shifts in rainfall patterns, temperature increases, and more frequent heat waves are negatively affecting fruit production in this region (Calzadilla, 2014). These effects of climate change are reducing both fruit yield and quality.

Sensitivity levels of some fruit species to climate change

Different fruit species exhibit varying levels of sensitivity to the diverse effects of climate change. Understanding these differences in sensitivity is crucial for developing effective and species-specific adaptation strategies.

Apple

Chilling hour requirements: Apple trees need to meet a specific period of chilling hours (usually below 7°C) during the winter season. This chilling process is vital for the trees to break dormancy and initiate regular flowering in the spring (Ramírez & Kallarackal, 2015; Salama *et al*., 2021). In case of mild winters, the accumulation of necessary chilling hours may decrease (González-Martínez *et al*., 2025; Ramírez & Kallarackal, 2015). This can lead to late or irregular opening of buds, reduced fruit set, and consequently, yield declines (Luedeling *et al*., 2011; Rodríguez *et al*., 2021; Salama *et al*., 2021).

High temperature stress: High temperature stress can cause sunburn, a decrease in color development, and a reduction in sugar content in fruits. Prolonged exposure to high solar radiation—particularly during summer—can elevate fruit surface temperatures well above ambient air temperature, leading to sunburn, which is one of the visible symptoms of climate change impacts on fruit quality (Bacelar *et al.,* 2024).

Risk of frost damage: The early onset of spring temperatures due to global warming can lead to early bud break in apple trees. This significantly increases the risk of damage to sensitive apple blossoms from late spring frosts and can cause severe crop losses (Lamichhane, 2021).

Water scarcity: Apple trees need sufficient water for healthy growth and quality fruit development (El Jaouhari *et al*., 2018). Drought conditions can lead to a reduction in fruit size, a decrease in yield, and a decline in fruit quality, including increased firmness, reduced soluble solids content, poor color development, and imbalanced acidity (Ameen *et al*., 2023).

Pests and diseases: Warmer climatic conditions can facilitate the spread of some pests and diseases, such as the codling moth and apple scab (Moinina *et al*., 2019). Temperature increases accelerate the life cycles of some pest species, allowing them to produce more generations per year. Changes in humidity levels can also affect the frequency of fungal diseases (Ghini *et al*., 2011). For example, an increase in rainfall in some regions can increase the risk of apple scab disease (Moinina *et al*., 2019). Therefore, it is of great importance to consider the complex interactions between temperature, humidity, and pest/disease dynamics (Moinina *et al*., 2019).

Other fruit species

Stone fruits: Similar to apples, stone fruits such as peaches, cherries, and plums also require a certain chilling period (Fadón *et al*., 2020) and are susceptible to high temperature stress, which can negatively affect their fruit set, fruit size, and fruit quality. Changes in rainfall patterns can also significantly affect stone fruit production (Kourgialas & Karatzas, 2016).

Citrus: Citrus species such as oranges, lemons, and grapefruits are generally more tolerant to higher temperatures compared to temperate climate fruits. However, climate change can also affect citrus production. The availability of water resources is of great importance for citrus cultivation, as citrus trees need significant amounts of water, especially through irrigation (Fares *et al*., 2017). Deviations in rainfall patterns and an increased risk of drought can significantly reduce citrus yields. In addition, some citrus pests and diseases, such as citrus greening disease, can be further exacerbated by temperature increases (Ghini *et al*., 2011).

Berries: Berry species such as strawberries, blueberries, and raspberries are particularly sensitive to temperature fluctuations (Nezhadahmadi *et al*., 2015). Temperature changes can affect fruit set, size, quality, and yield (Nezhadahmadi *et al*., 2015). The adequacy of water resources is also a critical factor for berry production. Since different berry species need different climatic conditions, the specific requirements of each species should be evaluated separately (Nezhadahmadi *et al*., 2015).

Grapes (wine and table grapes): Grapevines are quite sensitive to temperature changes. Temperature can affect the composition of grape berries (sugar content, acidity, etc.) and therefore wine quality. Changes in rainfall patterns can also affect grape yields (Rogiers *et al*., 2022).

Tropical fruits (mango, banana, papaya, avocado): Tropical fruit species such as mango, banana, papaya, and avocado exhibit a wide spectrum of sensitivity to the effects of climate change (Nath *et al*., 2018). While some tropical fruits, such as mango (Lauri *et al*., 2013), are relatively tolerant to high temperatures, others, such as bananas (Van Asten *et al*, 2011), are more sensitive to changes in rainfall patterns. Avocado, on the other hand, while showing a certain tolerance to high temperatures, needs a significant amount of water and is therefore vulnerable to drought and flood conditions (Taleb *et al*., 2022).

Adaptation and mitigation strategies

Coping with the complex and multidimensional challenges of global warming on fruit production requires a two-pronged strategic approach: mitigation efforts focused on reducing greenhouse gas emissions and adaptation strategies aimed at adapting to changing climatic conditions.

Climate change mitigation strategies (reducing greenhouse gas emissions)

While adaptation strategies aim to adapt to the inevitable effects of climate change, mitigation strategies focus on the root causes of climate change by reducing greenhouse gas emissions (Malhi *et al*., 2021). In the agricultural sector, mitigation strategies to reduce greenhouse gas emissions include various practices:

Adoption of sustainable agricultural practices: The widespread adoption of sustainable farming techniques can significantly reduce greenhouse gas emissions from agricultural activities (Baldock *et al*., 2012):

- **No-till or reduced tillage:** Practices that minimize or completely eliminate tillage reduce the amount of carbon dioxide released from the soil into the atmosphere and improve soil health. No-till or reduced tillage methods help carbon to be stored in the soil for longer and minimize soil erosion (Powlson *et al*., 2014);
- **Cover cropping:** Planting cover crops between fruit tree rows or during fallow periods after crop harvest significantly improves soil health, reduces soil erosion, and sequesters carbon from the atmosphere into the soil (Kaye & Quemada, 2017). Cover crops also positively affect soil water permeability and nutrient cycling (Scavo *et al*., 2022);
- **Efficient fertilizer use:** Optimizing the application rates and timing of fertilizers is an effective method to reduce emissions of nitrous oxide (N_2O), which is a potent greenhouse gas (Thapa *et al*., 2016). Precision agriculture technologies and soil-based fertilization allow farmers to use fertilizers more efficiently;
- **Improved manure management techniques:** Proper storage and processing of livestock manure can reduce greenhouse gas emissions such as methane (CH_4) and nitrous oxide (N_2O) (Thapa *et al*., 2016). Technologies such as anaerobic digestion and composting are effective manure management techniques for reducing greenhouse gas emissions (Zhang, Dou *et al*., 2013).

Use of renewable energy sources: Shifting to renewable energy sources such as solar energy, wind energy, or biogas in agricultural enterprises can significantly reduce greenhouse gas emissions from agricultural activities by reducing dependence on fossil fuels (Bilgili *et al*., 2024):

- **Solar energy systems:** Solar panels can be used to meet the energy needs of irrigation systems, farm buildings, and other on-farm energy needs, thereby reducing dependence on fossil fuel-based electricity (Bilgili *et al*., 2024);
- **Wind energy plants:** Wind turbines can generate electricity to meet the energy needs of farms, especially in regions with high wind energy potential (Bilgili *et al*., 2024);
- **Biogas production facilities:** Biogas production from anaerobic fermentation of agricultural waste and animal manure provides a renewable energy source that can be used for heating, electricity generation, and even as a transportation fuel (Alengebawy *et al*., 2024).

Preventing food loss and waste: Minimizing losses and waste occurring throughout the food chain plays a critical role in reducing greenhouse gas emissions from food production, processing, transportation, and disposal processes (Tang, 2020):

- **Improving harvesting and storage techniques:** Using advanced harvesting techniques, establishing modern storage facilities, and developing efficient transportation infrastructure to reduce postharvest crop losses can significantly reduce food waste (Moretti *et al*., 2010; Siddiqui *et al*., 2015);
- **Consumer awareness and education efforts:** Raising consumer awareness about food waste and disseminating practical information to reduce food waste at home can significantly contribute to reducing the overall amount of food waste (Reisch *et al*., 2021).

Atmospheric carbon sequestration in soil: Implementing practices to increase carbon sequestration in agricultural soils is an important strategy in the fight against climate change (Powlson *et al*., 2011). Methods such as afforestation, reforestation, and agroforestry contribute to the mitigation of climate change by sequestering carbon dioxide from the atmosphere into the soil (Baldock *et al*., 2012; Ghale *et al*., 2022):

- **Agroforestry systems:** Integrating trees into fruit orchards or vineyard areas (agroforestry) increases carbon sequestration as well as improving soil health and providing various ecological benefits (Ghale *et al.*, 2022). Agroforestry systems support biodiversity and create suitable habitats for beneficial insects and pollinators (Baldock *et al.*, 2012; Ghale *et al.*, 2022);

- **Afforestation and reforestation projects:** Planting trees on agriculturally unsuitable or marginal lands or converting idle agricultural lands into forest areas can significantly increase the storage of carbon from the atmosphere in the soil (Doelman *et al.*, 2020; Wang *et al.*, 2022).

Climate change adaptation strategies (adapting to changing climatic conditions)

Crop management strategies: Implementing effective crop management strategies to adapt to changing climatic conditions is crucial. These strategies must be informed by detailed ecophysiological studies that explore how different fruit species respond to variables such as temperature, water availability, and solar radiation (Fischer *et al.*, 2016). For instance, research on apple trees has shown that elevated temperatures reduce photosynthetic rates and increase respiration, affecting fruit quality and yield (Ameen *et al.*, 2023). Likewise, in peaches, high day and night temperatures have been linked to impaired fruit coloration and firmness (Jayasooriya *et al.*, 2025). Therefore, integrating findings from plant ecophysiology into crop management—such as adjusting planting dates, selecting climate-resilient cultivars, or optimizing irrigation schedules—is essential to ensure sustainable fruit production under changing climatic conditions.

- **Development and use of heat and drought-resistant varieties:** Developing and disseminating fruit varieties that exhibit high tolerance to temperature and drought stress is one of the basic adaptation strategies (Haokip *et al.*, 2020; Sayyad-Amin, 2022). This process includes the following approaches:
  - » **Traditional breeding methods:** Conventional breeding techniques can be effectively used to select and cross fruit varieties with desirable traits such as temperature and drought tolerance (Chapman *et al.*, 2012);
  - » **Marker-assisted selection (MAS):** Molecular markers can be used to identify gene regions associated with stress tolerance in plants (Chapman *et al.*, 2012; Gogorcena *et al.*, 2020). In this way, breeding programs can be carried out more quickly and efficiently;
  - » **Genetic engineering and CRISPR-Cas9 technology:** Gene editing technologies such as CRISPR-Cas9 offer the potential to increase stress tolerance by precisely altering the genetic structure of fruit trees (Bacelar *et al.*, 2024; Ndudzo *et al.*, 2024). These technologies can accelerate the development of climate-resistant fruit varieties.

- **Increasing irrigation efficiency:** In regions experiencing water scarcity, in particular, the implementation of water-saving irrigation systems such as drip irrigation and micro-sprinkling is very important (Peng *et al.*, 2024; Romero *et al.*, 2006). Rainwater harvesting and efficient water storage can also contribute to sustainable water management for fruit production (Zhang *et al.*, 2019; Zhang, Zhang *et al.*, 2018). In addition, the use of Regulated Deficit Irrigation (RDI)—a strategy that applies water below full crop evapotranspiration during less sensitive growth stages—has shown promising results in fruit crops such as pear, enhancing water use efficiency without significantly compromising yield or fruit quality (Vélez-Sánchez *et al.*, 2023).
  - » **Drip irrigation systems:** Drip irrigation minimizes water losses through evaporation and surface runoff by delivering water directly to the plant root zone (Peng *et al.*, 2024). This method significantly increases water use efficiency;
  - » **Micro-sprinkling systems:** Micro-sprinkling systems provide effective irrigation using less water than traditional sprinkler systems and contribute to water conservation (Taleb *et al.*, 2022);
  - » **Rainwater harvesting and storage:** Collecting and storing rainwater provides an additional water source for irrigation, reducing dependence on groundwater and surface water resources. Rainwater harvesting is a crucial practice in sustainable water management (Ward, 2014; Zhang *et al.*, 2019; Zhang, Zhang *et al.*, 2018);
  - » **Development of water storage infrastructure:** Improving water storage infrastructure such as dams, ponds, and groundwater storage facilities can help ensure a reliable supply of water during drought periods (Shakoor & Ullah, 2024).

- **Shading structures and other protective measures:** The use of shading nets, reflective mulches, and other protective materials can help reduce heat stress by protecting fruit trees from extreme heat and adverse weather conditions (Mditshwa *et al.*, 2019).

- » **Shading nets:** Shading nets can reduce the temperature of the canopy above fruit trees by reducing solar radiation, thereby alleviating heat stress (Kalcsits *et al*., 2017);
- » **Reflective mulches:** Reflective mulch materials can reduce soil temperature and heat stress on plants by reflecting sunlight away from trees and soil (Kalcsits *et al*., 2017);
- » **Windbreakers:** Planting windbreak rows of plants around orchards protects trees from strong winds, reducing fruit drop and physical damage to trees (Chawla *et al*., 2011; Veste *et al*., 2020);
- » **Hail nets:** Protective nets against hail effectively protect fruits from hail damage, preventing significant crop losses that may occur during hailstorms (Bal *et al*., 2014; Brglez Sever *et al*., 2015).

- **Adjusting planting times and growing seasons:** Optimizing planting dates and growing seasons can help synchronize fruit production with more suitable climatic conditions. However, such adjustments must be based on the systematic collection and analysis of long-term climatic data, including temperature trends, rainfall patterns, and the timing of frost events. Agroclimatic modeling tools and decision support systems are increasingly used to assess the suitability of specific planting windows, helping to avoid critical stress periods and align phenological stages with favorable environmental conditions (IPCC, 2021; Osorio-Marín *et al*., 2024). For example, in temperate regions, shifting planting schedules by even one or two weeks has been shown to reduce exposure to early-season heatwaves or late frosts, thereby improving fruit set and quality (Fischer *et al*., 2016).
  - » **Delayed planting practices:** In some regions, delaying planting dates beyond the regular schedule can help avoid late spring frosts or extreme heat stress in the summer months (Campoy *et al*., 2011; Chawla *et al*., 2011);
  - » **Flexibility in variety selection:** Choosing fruit varieties with different chilling requirements or different ripening times is one way to better adapt to changing climatic conditions (Malhotra, 2017);
  - » **Second crop or intercropping systems:** In regions where climatic conditions are suitable, implementing second crop or intercropping systems can maximize resource use and potentially increase overall productivity (Burgess *et al*., 2022).

- **Strengthening integrated pest and disease management (IPM) strategies:** In changing climatic conditions, implementing effective pest and disease management strategies is vital for sustainable fruit production.
  - » **Integrated pest management (IPM) approaches:** IPM strategies offer significant advantages to fruit growers in coping with the effects of climate change (Bacelar *et al*., 2024; Moinina *et al*., 2019):
    - › **Biological control methods:** The use of natural enemies such as predatory insects and parasitoids should be encouraged to control pest populations naturally (Bacelar *et al*., 2024);
    - › **Cultural measures:** Cultural methods such as crop rotation (where appropriate), sanitation practices, and the use of resistant varieties play an important role in preventing pest and disease outbreaks (Gruda *et al*., 2019);
    - › **Targeted pesticide applications:** When the use of chemical pesticides is unavoidable, only necessary and targeted applications should be preferred, in a way that minimizes adverse effects on the environment and protects beneficial organisms (Zhou *et al*., 2024).

- **Promoting biological control:** Expanding the use of natural enemies to control pests offers a more sustainable approach by reducing dependence on chemical pesticides (Bacelar *et al*., 2024; Thomson *et al*., 2010):
  - » **Use of predatory insects and mites:** Increasing the populations of predatory insect and mite species that feed on fruit pests or releasing them into orchards can help reduce pest pressure naturally (Thomson *et al*., 2010);
  - » **Use of parasitoids:** Beneficial organisms such as parasitoid wasps can be effective in controlling fruit pests by parasitizing them and controlling their populations (Prasad & Bambawale, 2010; Thomson *et al*., 2010);
  - » **Biological control with microbial agents:** Microbial agents such as bacteria like *Bacillus thuringiensis* (Bt), beneficial fungi, or viruses can be used as biological pesticides against pests and offer an environmentally friendly alternative (Sangiorgio *et al*., 2020; Thomson *et al*., 2010).

- **Soil health improvement management:** Adopting practices to improve soil health is critical to increase the resistance of fruit trees to climate change.

- **Strategies to increase soil organic matter:** Increasing soil organic matter content forms the basis of soil health and resilience to climate change (Lal, 2013). Healthy soils are more resistant to drought and erosion and contribute to long-term sustainability for fruit production (Sierra *et al*., 2015):
  - **Cover crops:** Cover crops significantly enrich soil organic matter content in addition to preventing soil erosion and increasing carbon sequestration (Kaye & Quemada, 2017; Scavo *et al*., 2022);
  - **Compost applications:** Regularly applying compost to orchards and vineyards increases the water-holding capacity of the soil, improves soil structure, and raises soil organic matter levels (Montanaro *et al*., 2017);
  - **No-till or reduced tillage:** Agricultural techniques that do not till the soil or till it at a minimum level help protect organic matter without disrupting the soil structure and support soil health (Montanaro *et al*., 2017; Powlson *et al*., 2014).

- **Policy and economic support mechanisms:** The effective use of policy and economic tools is of great importance to promote and support adaptation to climate change in the fruit growing sector.
  - **Subsidy and incentive programs:** Governments can implement various subsidy and incentive programs to encourage farmers to adopt sustainable agricultural practices and invest in climate-resistant technologies. These programs help farmers finance the adaptation process and manage risks:
    - **Financial support for sustainable practices:** Subsidies, grant programs, and cost-sharing mechanisms play a crucial role in alleviating the financial burden faced by farmers as they transition to sustainable agricultural practices and invest in climate-resistant technologies (Piñeiro *et al*., 2020);
    - **Tax advantages for climate-friendly investments:** Practices such as tax deductions and tax exemptions can encourage farmers to modernize irrigation systems, build shading structures, and invest in other adaptation measures (Beddington *et al*., 2011).

- **Increasing research and development (R&D) investments:** Continuous investment in R&D activities is essential for promoting innovation in precision agriculture and smart farming techniques in fruit cultivation (Lee *et al*., 2014). These investments accelerate the development of new technologies and methods, thereby enhancing the sector's competitiveness.
  - **Increasing public R&D funds:** Increasing public R&D funds for research in critical areas such as developing climate-resistant fruit varieties, improving water efficiency techniques, and effective pest and disease management strategies is vital (Beddington *et al*., 2011);
  - **Public-private sector collaborations:** Collaboration and partnerships between public research institutions and private sector companies can accelerate innovation in smart agriculture technologies, ensuring that the developed new technologies reach farmers more quickly (Manos *et al*., 2014; Zhang *et al*., 2018).

- **Developing climate risk insurance systems:** Establishing and disseminating climate insurance programs can help fruit growers manage financial risks arising from climate change-related crop losses.
  - **Crop insurance against extreme weather events:** Insurance programs that cover crop losses caused by extreme weather events such as heatwaves, droughts, frost events, and hailstorms can provide an important safety net for fruit producers (Mârza *et al*., 2015);
  - **Index-based insurance systems:** Index-based insurance systems that make payments based on specific weather parameters, such as rainfall amounts or temperature values, can offer a more efficient and cost-effective alternative to traditional insurance methods (Ricome *et al*., 2017).

- **Strengthening education and extension activities:** Effectively delivering information and technology to farmers and capacity building efforts are among the keys to a successful adaptation process.
  - **Modernization of agricultural extension services:** Strengthening agrarian extension services and supporting them with modern methods play a critical role in delivering up-to-date information and training on climate-smart agriculture practices to farmers (Asfaw *et al*., 2019);
  - **Farmer field schools and practical training:** Farmer field schools contribute to the dissemination of sustainable agricultural techniques and climate adaptation strategies by providing practical training opportunities and promoting the sharing of knowledge (Davis *et al*., 2012);
  - **Online information resources and decision support systems:** Developing online information platforms and decision support tools can provide farmers with easily accessible climate data, best practice examples, and information to assist them in decision-making processes (Zhai *et al*., 2020).

Future perspectives and necessary measures

The future of fruit production in an increasingly warming world depends on implementing effective adaptation strategies and joint efforts to reduce greenhouse gas emissions. The following key recommendations should be considered to increase the long-term sustainability and resilience of fruit production to climate change:

Priority should be given to research on climate-resistant fruit varieties: Future research and development efforts should focus on developing fruit varieties that are particularly tolerant to temperature and drought, resistant to pests and diseases, able to use water and nutrient resources efficiently, and able to maintain or improve fruit quality even under changing climatic conditions (Chapman *et al.*, 2012; Nath *et al.*, 2018). Advanced breeding technologies such as marker-assisted selection and genetic engineering should be used effectively to accelerate the development and dissemination of climate-resistant varieties (Gogorcena *et al.*, 2020; Muranty *et al.*, 2014).

Investments should be made in efficient irrigation and water management infrastructure: Increasing water storage capacity through dams, ponds, and groundwater storage projects is of critical importance (Shakoor & Ullah, 2024). The adoption of water-saving irrigation systems such as drip irrigation and micro-sprinkling should be supported and disseminated through incentive programs and technical support services (Peng *et al.*, 2024; Romero *et al.*, 2006). Rainwater harvesting projects should be encouraged and supported at both the farm and community level (Zhang, Zhang *et al.*, 2018; Zhang *et al.*, 2019). Regulatory and economic mechanisms such as water pricing policies and water audit programs should be implemented to increase water use efficiency in agriculture (Peng *et al.*, 2024; Romero *et al.*, 2006).

The adoption of sustainable agricultural practices should be encouraged: Practices to protect and improve soil health should be disseminated through financial incentives and technical assistance mechanisms to encourage farmers to adopt reduced tillage, cover crops, composting, and other soil health-improving practices (Beddington *et al.*, 2011; Piñeiro *et al.*, 2020). Integrated pest management (IPM) strategies should be promoted and facilitated through research studies, extension services, and supportive legal regulations (Gvozdenac *et al.*, 2022). The potential of supporting and disseminating organic farming systems should be evaluated. Organic farming offers an approach that prioritizes soil health, biodiversity, and the reduction of synthetic inputs (Muller *et al.*, 2017).

Cooperation between researchers, extension experts, policy makers and fruit growers should be strengthened: Interdisciplinary research projects involving experts from different disciplines (breeders, agricultural engineers, soil scientists, entomologists, plant pathologists, economists and social scientists) should be encouraged to tackle the complex challenges of climate change in the fruit growing sector (Reyes-García *et al.*, 2019). Extension and information networks should be strengthened to effectively disseminate research results and best practices to fruit growers (Below *et al.*, 2012). Actively involving fruit growers, other stakeholders in the sector, and policymakers in the development and implementation of climate adaptation strategies is critical to increasing the relevance and adoption of these strategies.

Development and implementation of policies supporting adaptation to climate changes in the fruit sector: Climate adaptation plans should be prepared for the fruit growing sector at national and regional level, and sector-specific targets, strategies and actionable steps should be defined in detail (Zhang *et al.*, 2018). Policy incentives such as subsidies, tax breaks and insurance schemes should be used effectively to promote climate adaptation and greenhouse gas (GHG) emissions reductions (Del Pozo *et al.*, 2019; Ghale *et al.*, 2022). Regulatory frameworks should be established that prioritise environmental sustainability objectives in fruit production, such as sustainable management of water resources, reduction of pesticide use, and protection of soil health.

Conclusions

Global warming presents significant challenges to fruit production worldwide. Rising temperatures, shifting precipitation patterns, and increased frequency of extreme weather events are impacting fruit yields, quality, and geographic distribution. Adapting to these changes is crucial for ensuring the long-term sustainability of the fruit industry. This requires a multifaceted approach, including the development of heat- and drought-tolerant varieties, improving irrigation efficiency, implementing sustainable farming practices, and adopting integrated pest and disease management strategies. Mitigating climate change through the reduction of greenhouse gas emissions is also essential. Policy interventions, such as subsidies, incentives, and research funding, can play a critical role in supporting farmers in their efforts to adapt to a changing climate. By taking proactive steps to address these challenges, we can help ensure the future of fruit production and the availability of nutritious and delicious fruits for generations to come.

Conflict of interest statement

The author declares that there is no conflict of interests regarding the publication of this article.

Author´s contributions

AI prepared the manuscript and approved its final version.

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