



## Impacts of climate change on the phenology and pollination of temperate fruit species: implications for sustainable fruit growing

Impactos del cambio climático en la fenología y la polinización de especies frutales de clima templado: implicaciones para el cultivo sostenible de frutales

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**Cherry flowers.**  
Photo: A. İkinci

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## ABSTRACT

Global climate change poses significant challenges to temperate fruit production, particularly by disrupting pollination services essential for fruit yield and quality. This review synthesizes current scientific literature to evaluate how climate change influences the phenology and pollination of temperate fruit species. Rising temperatures are accelerating key phenological events, such as budburst and flowering, in fruit trees. These shifts frequently cause temporal mismatches with the activity periods of insect pollinators. As a result, pollination efficiency declines, leading to reduced fruit set and yield. The adverse effects of climate change on pollinators are further intensified by habitat loss, pesticide exposure, and diseases, contributing to biodiversity loss and population decline. The cumulative impact of these stressors threatens the sustainability of fruit production. This paper also explores various adaptation strategies aimed at minimizing the risk of pollination failure. These include selecting climate-resilient cultivars, conserving and enhancing pollinator habitats, implementing integrated pest management, and optimizing orchard practices. Supporting wild pollinators alongside managed species such as honeybees can provide ecological resilience against phenological mismatches. Furthermore, long-term regional monitoring and modeling of plant-pollinator interactions are essential for future risk assessments. In conclusion, ensuring sustainable fruit production in a changing climate requires a holistic approach integrating genetic, ecological, and agronomic strategies. Collaborative efforts by researchers, growers, and policymakers are crucial to safeguard pollination services and build climate-resilient fruit systems.

**Additional key words:** global warming; phenological mismatch; ecosystem services; food security; pollinator decline; adaptation; orchards; *Apis mellifera*.

## RESUMEN

El cambio climático global plantea desafíos significativos para la producción de frutales en zonas templadas, especialmente al alterar los servicios de polinización esenciales para el rendimiento y la calidad de los frutos. Esta revisión sintetiza la literatura científica actual para evaluar cómo el cambio climático influye en la fenología y la polinización de especies frutales de clima templado. El aumento de las temperaturas está acelerando eventos fenológicos clave, como la brotación y la floración, en los árboles frutales. Estos cambios provocan con frecuencia desajustes temporales con los periodos de actividad de los insectos polinizadores. Como resultado, la eficiencia de la

polinización disminuye, lo que conduce a una reducción del cuajado de frutos y del rendimiento. Los efectos adversos del cambio climático sobre los polinizadores se ven agravados por la pérdida de hábitat, el uso de pesticidas y la propagación de enfermedades, contribuyendo a la pérdida de biodiversidad y al declive poblacional. El impacto acumulativo de estos factores amenaza la sostenibilidad de la producción frutícola. Este trabajo también explora diversas estrategias de adaptación orientadas a minimizar el riesgo de fallos en la polinización. Entre ellas se incluyen la selección de cultivares resilientes al clima, la conservación y mejora de los hábitats de los polinizadores, la implementación del manejo integrado de plagas y la optimización de las prácticas agrícolas. El fomento de polinizadores silvestres junto con especies manejadas como la abeja melífera puede aportar resiliencia ecológica frente a los desajustes fenológicos. Además, el monitoreo regional a largo plazo y la modelización de las interacciones planta-polinizador son esenciales para futuras evaluaciones de riesgo. En conclusión, garantizar una producción frutícola sostenible en un clima cambiante requiere un enfoque holístico que integre estrategias genéticas, ecológicas y agronómicas. Los esfuerzos colaborativos entre investigadores, productores y responsables de políticas públicas son fundamentales para proteger los servicios de polinización y construir sistemas frutícolas resilientes al clima.

**Palabras clave adicionales:** calentamiento global; desajuste fenológico; servicios ecosistémicos; seguridad alimentaria; declive de los polinizadores; adaptación; huertos; *Apis mellifera*.

## INTRODUCTION

Global climate change stands as one of the most significant environmental challenges confronting our planet, exerting profound and widespread impacts on agricultural systems (Walther *et al.*, 2002; Polce *et al.*, 2014). Approximately 35% of global agricultural production is directly contingent upon pollinator activity, with the yield and quality of numerous fruit, vegetable, and seed crops relying on efficient pollination services primarily provided by various insects, particularly bees (Klein *et al.*, 2007; Winfree and Kremen, 2009; Abrol, 2012). This essential ecosystem service is of paramount importance for both food security and biodiversity conservation (Abrol, 2012; IPBES, 2016). In fruit trees, pollination, the transfer of pollen from the anther to the stigma of a flower, constitutes a critical biological process that initiates fertilization and subsequent fruit development. While this process can be mediated by wind, water, or biotic agents, insect pollinators play the most crucial role in commercial orchards

(Winfrey and Kremen, 2009; Abrol, 2012). Pollination efficiency is directly correlated with fruit quality, seed viability, and overall agricultural productivity.

Climate change, manifested through rising temperatures, altered precipitation regimes, and increased frequency of extreme weather events, possesses the potential to impact plant-pollinator interactions at multiple levels (Hegland *et al.*, 2009; Byers, 2017; Trunschke *et al.*, 2024). One of the most salient consequences of these changes is the temporal shifts in the phenological stages of plants and the activity periods of pollinators (Bartomeus *et al.*, 2013; Renner and Zohner, 2018). Temperate fruit species complete critical phenological stages, such as budburst and flowering, by responding to climatic cues like winter chilling accumulation and spring temperature increases (Luedeling *et al.*, 2009). However, global warming is inducing earlier occurrences of these phenological events (Wolfe *et al.*, 2005; Chitu and Paltineanu, 2020; Osorio-Marín *et al.*, 2024).

While pollinator insect phenology also exhibits sensitivity to climatic changes, their responses may differ from those of plants (Hegland *et al.*, 2009; Forrest, 2016). These differential response rates can lead to phenological mismatches, where pollinators may not yet be active when plants are flowering, or conversely, plant flowering may be delayed (delayed flowering) in relation to pollinator emergence (Bartomeus *et al.*, 2013; Renner and Zohner, 2018; Kumar *et al.*, 2024). Phenological asynchrony poses a significant threat to temperate fruit cultivation by leading to insufficient pollination and, consequently, reductions in fruit set and yield (Polce *et al.*, 2014; Ramírez and Kallarackal, 2018a).

This article reviews the impacts of climate change on the phenology and pollination dynamics of temperate fruit species, drawing upon existing scientific literature. It addresses how climate change-induced phenological shifts alter the synchronization of plant-pollinator interactions and explores their potential consequences for fruit set and yield. Furthermore, potential adaptation and management strategies aimed at mitigating these adverse effects are discussed. This study holds significance for understanding the complex ramifications of climate change on temperate fruit cultivation and for developing sustainable production systems.

## **IMPACT OF CLIMATE CHANGE ON THE PHENOLOGY OF TEMPERATE FRUIT SPECIES**

The phenology of temperate fruit species is intrinsically linked to annual climatic cycles, where the timing of stages such as budburst, flowering, and fruit development is influenced by factors including temperature and chilling requirements (Ramírez and Kallarackal, 2015). These

plants fulfill their chilling requirements by being exposed to specific durations of low temperatures during winter months, a prerequisite for the initiation of growth in spring (Luedeling *et al.*, 2009). The global increase in temperatures is leading to insufficient winter chilling periods and earlier spring temperature rises in many temperate fruit-growing regions (Luedeling *et al.*, 2009; Luedeling *et al.*, 2011). Inadequate winter chilling delays the satisfaction of dormancy requirements and disrupts the regularity of the flowering period (Osorio-Marín *et al.*, 2024). This situation poses a significant challenge, particularly for cultivars with high chilling requirements (Luedeling *et al.*, 2009; Atkinson *et al.*, 2013).

Numerous studies have demonstrated that climate change affects the phenological stages of various temperate fruit species, including apple, pear, cherry, and olive (Wolfe *et al.*, 2005; Benlloch-González *et al.*, 2018; Chitu and Paltineanu, 2020; Paltineanu and Chitu, 2020; Osorio-Marín *et al.*, 2024). The general trend indicates a significant advancement of spring phenological stages (budburst, flowering onset, full bloom) in recent years (Wolfe *et al.*, 2005; Menzel *et al.*, 2006; Chitu and Paltineanu, 2020). For instance, a study conducted in a temperate-continental climate reported a notable advancement in the flowering time of apple and pear trees over the years, correlating with increased spring temperatures (Chitu and Paltineanu, 2020). Additionally, global evaluations of phenological models, particularly in apple, have been conducted to improve adaptation strategies under changing climate conditions (Darbyshire *et al.*, 2017). Similarly, climate change-induced shifts in flowering stages have been observed in cherry trees (Paltineanu and Chitu, 2020). For olive trees, high temperatures have been specifically identified as directly impacting flowering (Benlloch-González *et al.*, 2018).

Phenological responses of different fruit species, and even distinct cultivars within the same species, to climatic variations are highly variable (Hegland *et al.*, 2009; Renner and Zohner, 2018). These differences are influenced by factors such as local climatic conditions, genetic predisposition (Hegland *et al.*, 2009; Luedeling *et al.*, 2011), soil type, and cultural practices (Ramírez and Kallarackal, 2015; Fischer *et al.*, 2021). Insufficient chilling leads to irregular and weak budburst, extended flowering duration, and reduced floral quality, thereby negatively affecting pollination success (Ramírez and Kallarackal, 2015). Moreover, early flowering induced by climate change increases the vulnerability of plants to late spring frosts, which is considered a critical risk factor that can result in substantial yield losses (Chitu and Paltineanu, 2020).

In conclusion, climate change significantly impacts the phenology of temperate fruit species, accelerating flowering times and creating additional problems such as insufficient chilling. These phenological shifts heighten the risk of potential mismatches with pollinator activity periods, thereby creating serious challenges for sustainable fruit production.

## **IMPACT OF CLIMATE CHANGE ON POLLINATOR POPULATIONS AND ACTIVITY**

Insect pollinators (Hymenoptera: Apoidea), which are fundamental for the productivity of temperate fruit orchards, exhibit high sensitivity to the effects of climate change (Abrol, 2012; Vanbergen and Insect Pollinators Initiative, 2013). Rising temperatures, altered precipitation regimes, and extreme weather events can modify the size, distribution, and timing of life cycle stages of pollinator populations (Hegland *et al.*, 2009; Byers, 2017). Notably, bees (Hymenoptera: Apoidea), which play a key role in the pollination of temperate fruit species, are significantly affected by these changes (Abrol, 2012; Bartomeus *et al.*, 2013). Figure 1 illustrates the diversity of temperate fruit tree flowers and highlights bee visitation, emphasizing the critical role of insect pollinators in orchard ecosystems.

Studies indicate that climate change is altering the phenology of numerous pollinator insect species (Hegland *et al.*, 2009; Forrest, 2016). Particularly in species that emerge in spring, an advancement in activity initiation dates has been observed, paralleling increasing temperatures (Parmesan, 2006; Forrest, 2016; Olsen *et al.*, 2022). However, the variability in phenological responses of different pollinator species to temperature changes can lead to phenological asynchrony, where the plant flowering period does not sufficiently overlap with the times of peak pollinator activity and effectiveness (Bartomeus *et al.*, 2013; Renner and Zohner, 2018).



**Figure 1. Flowers of temperate fruit species including cherry, apricot, apple, peach, pear, and quince.**

The impacts of climate change on pollinator populations are not limited to phenological shifts alone. Climate change, compounded by other pressures such as habitat loss and fragmentation, pesticide use, and diseases, is contributing to population declines and reduced species diversity in many pollinator taxa (Goulson *et al.*, 2015; Sánchez-Bayo and Wyckhuys, 2019; Vasiliev and Greenwood, 2021; Sabbahi, 2022). Changes in the distributions and range contractions of some wild bee species have been reported in connection with climate change (Parmesan, 2006; Franzén and Öckinger, 2012; Kerr *et al.*, 2015). A reduction in pollinator diversity can jeopardize the reliability of pollination services required in temperate fruit orchards, as different pollinator species may be active at different times or exhibit varying floral visitation preferences (Winfree and Kremen, 2009; Bartomeus *et al.*, 2013). Research indicates that honeybees (*Apis mellifera*) contribute significantly to yield increases in many fruit species. However, studies have shown that wild pollinators can enhance fruit set regardless of honeybee abundance, highlighting the need to support pollinator diversity (Garibaldi *et al.*, 2013, Rodríguez-Torres *et al.*, 2025). These contributions and the necessary honeybee colony densities vary by species (Tab. 1). Climate

change is altering the geographic distribution of pollinator species, leading to pollinator loss in certain regions. A study conducted in Brazil predicted that the probability of pollinator existence would decrease by 13% by 2050 (Giannini *et al.*, 2017).

**Table 1. Pollination requirements, expected yield increase with bee pollination, and required bee colony numbers per hectare for various fruit species.**

Fruit crops	Pollination requirements	Expected increase in yield due to cross-pollination (%)	Expected increase in yield of some fruit crops due to bee pollination (%)	Bee colonies needed per ha
Almond	Highly cross pollinated	20	50-75	5-8
Apple	Highly cross pollinated	20	18-69.5	2-3
Citrus	Often cross pollinated	20	7-223	2-3
Grape	Often cross pollinated	20	23-54	2-3
Guava	Cross pollinated	10	12-30	2-3
Litchi	Highly cross pollinated		453-10 246	2-3
Mango	Bee visit is helpful	3		2-3
Papaya	Pollen transfer is essential	10		2-3
Plums	Vary from self compatible to self incompatible		536-1655	2-3

Source: Adapted from Abrol (2012).

Pollinator activity is directly influenced by climatic factors such as temperature, humidity, and precipitation (Abrol, 2012). Abnormal weather conditions during the flowering period can reduce pollinator flight activity, thereby decreasing pollination rates (Abrol, 2012; Haokip *et al.*, 2020; Magnin *et al.*, 2025). Furthermore, increasingly frequent climate change-induced events like drought can adversely affect pollinators by reducing the availability of nectar and pollen resources (Ramírez and Kallarackal, 2015; Haokip *et al.*, 2020). High temperatures can physiologically impact pollinator physiology and behavior (Scaven and Rafferty, 2013). Global warming may also foster the emergence of harmful species, which can diminish pollinator health and reduce crop floral attractiveness.

These changes in pollinator populations and activity levels under shifting climatic conditions possess the potential to diminish the availability and effectiveness of essential pollination services for temperate fruit species (Goulson *et al.*, 2015).

## IMPACT OF PHENOLOGICAL MISMATCH ON FRUIT SET AND YIELD

For achieving high fruit set and yield in temperate fruit species, synchronization between plant and pollinator phenological timing is of critical importance (Abrol, 2012). Climate change-induced advancement in plant phenology and alterations in pollinator activity periods threaten this synchronization, thereby increasing the risk of phenological asynchrony (Bartomeus *et al.*, 2013; Renner and Zohner, 2018). In cases of phenological mismatch, specifically when an insufficient number and diversity of active pollinators are present during the plant's flowering period, pollination remains inadequate (Memmott *et al.*, 2007).

Many temperate fruit species are highly dependent on insect pollination for successful reproduction (Polce *et al.*, 2014; Sheffield, 2014). The frequency and effectiveness of pollinator visits during the flowering period directly influence fruit set and, consequently, ultimate yield (Polce *et al.*, 2014; Sheffield, 2014). Phenological mismatch, such as when pollinators have not yet emerged during early flowering, can lead to significant reductions in fruit set by decreasing fertilization rates (Memmott *et al.*, 2007; Bartomeus *et al.*, 2013). Studies indicate that climate change-induced phenological mismatches can have adverse effects on the yield of various fruit species, including apple (Polce *et al.*, 2014), cherry (Paltineanu and Chitu, 2020), and olive (Benlloch-González *et al.*, 2018). In the UK, geographical mismatches between orchards and their pollinators are anticipated under future climate conditions, potentially leading to a loss of pollination services (Polce *et al.*, 2014).

The effects of phenological mismatch can be partially mitigated in ecosystems with high pollinator diversity (Bartomeus *et al.*, 2013). Diverse pollinator communities can stabilize pollination services under climate variability, and wild pollinators have been shown to significantly enhance fruit set even in the presence of abundant honeybee populations (Garibaldi *et al.*, 2013). Since different pollinator species tend to respond differentially to climatic changes, a richer pollinator community can provide an "insurance effect" by increasing the likelihood that at least one effective pollinator species will be active when the plant is flowering (Winfree and Kremen, 2009; Bartomeus *et al.*, 2013). For instance, certain species like native bees can buffer

the negative impacts of climate warming on honeybee pollination (Rader *et al.*, 2016). However, in regions where pollinator diversity is diminished, the adverse effects of phenological mismatch on yield may become more pronounced.

Furthermore, increasing temperatures and changing climatic conditions can affect the floral quality and nectar/pollen production of fruit trees; this, in turn, can alter floral attractiveness and visitation rates for pollinators (Abrol, 2012; Scaven and Rafferty, 2013). Temperatures above or below the optimal range negatively impact pollination, fertilization, and fruit set in temperate fruit trees (Rai *et al.*, 2015). While the optimal temperature range for species like pear, apple, cherry, and plum is generally between 20-25°C (Rai *et al.*, 2015), high temperatures exceeding this optimum lead to functional damage in floral-pollen structures, thereby hindering effective pollination and fertilization (Rai *et al.*, 2015; Ramírez and Kallarackal, 2018a). Studies have shown that temperatures above 24°C reduce pollen tube growth in *Prunus domestica* (DeCeault and Polito, 2010), and even extreme temperatures like 50°C prevented pollen germination in wild *Prunus* species (DeCeault and Polito, 2010). High temperatures can directly affect fertilization success and fruit set by reducing pollen viability or causing damage to pistils (Benlloch-González *et al.*, 2018; Ameen *et al.*, 2023). A study conducted by Ramírez and Davenport (2016) reported that mango pollen viability and germination rates decreased when temperatures exceeded approximately 30°C.

Within this framework, the potential for climate change-induced phenological shifts to cause plant-pollinator mismatches in temperate fruit orchards represents a significant risk factor for the sustainability of this sector. Potential reductions in fruit yield can lead to both economic losses and impacts on regional food security.

## ADAPTATION STRATEGIES

To mitigate the adverse effects of climate change on the pollination of temperate fruit species and ensure sustainable fruit growing in the future, the adoption of various adaptation strategies is imperative (Ramírez and Kallarackal, 2015). These strategies should encompass both cultivation-level practices and broader ecosystem management.

A crucial adaptation approach involves the selection and development of cultivars that are more resilient to climate change or can better adapt to changing conditions (Ramírez and Kallarackal, 2015). Considering regional climate change trends and phenological projections,

selection should prioritize cultivars that can better adapt to current and future climatic conditions, particularly those with low winter chilling requirements or greater phenological flexibility. Developing cultivars with low chilling requirements represents the most suitable solution for addressing the problem of insufficient chilling (Haokip *et al.*, 2020). The identification and utilization of genotypes appropriate for climate change scenarios within breeding programs will play a strategic role in preventing future yield losses (Ramírez and Kallarackal, 2015). Crop-specific studies assessing the impacts of climate change and evaluating adaptation strategies have proven useful in guiding regional responses. For instance, kiwifruit production systems have been comprehensively evaluated under climate stress, providing insights that may also benefit other temperate fruit crops (Rajan *et al.*, 2024). Furthermore, favoring cultivars whose flowering times are expected to synchronize better with future pollinator activity periods can help reduce the risk of phenological mismatch (Bartomeus *et al.*, 2013). Luedeling *et al.* (2011) and Gordo and Sanz (2010) suggest that adapting to changing climatic conditions in fruit cultivation necessitates the development of new cultivars, focusing production in regions where adequate chilling duration is ensured, or employing artificial chilling techniques.

Effective pollinator management is also a critical component of adaptation strategies. The timely placement of commercial pollinators (e.g., honeybee or bumblebee colonies) at sufficient densities within orchards during the flowering period can help ensure adequate pollination (Sheffield, 2014; Haokip *et al.*, 2020). However, beyond sole reliance on commercial colonies, it is also crucial to support natural pollinators, such as local wild bees (Winfree and Kremen, 2009; Abrol, 2012). For effective pollination management, the deployment of honeybee (*Apis mellifera*) colonies in accordance with the flowering periods of fruit species is of vital importance; detailed information on this matter (Tab. 2).

The conservation and enhancement of pollinator diversity offer an "insurance" mechanism against climate change-induced phenological shifts (Bartomeus *et al.*, 2013). The tendency of different pollinator species to respond differentially to climatic changes increases the likelihood that at least one effective species will be active when the plant is flowering (Bartomeus *et al.*, 2013). Establishing pollinator-friendly habitats within and around orchards (e.g., native flowering plant strips, areas of natural vegetation) can bolster wild bee populations, thereby enhancing the resilience of pollination services (Sheffield, 2014; Ramírez and Kallarackal, 2018b; Olsen *et al.*, 2022; Haokip *et al.*, 2020). Polyculture systems and cultivars with broad flowering windows

contribute to increased ecosystem resilience (Wolfe *et al.*, 2005). Wolfe *et al.* (2005) noted that late-flowering cultivars, such as 'Goldrush' apple, can compensate for phenological shifts. Furthermore, it is of vital importance to reduce the use of pesticides harmful to pollinators or to opt for safer alternatives, and to adjust application timing according to pollinator activity (Goulson *et al.*, 2015; Haokip *et al.*, 2020). Organic farming practices and integrated pest management (IPM) can enhance pollination efficiency by protecting pollinator populations (Haokip *et al.*, 2020).

Various horticultural practices employed in orchard cultivation can also play a role in climate change adaptation. Optimal irrigation and fertilization can improve floral quality and nectar/pollen production in stressed trees, thereby increasing their attractiveness to pollinators (Scaven and Rafferty, 2013). Active or passive protection methods against extreme weather events like early frost or excessive temperatures (e.g., misting, cover systems) can also be utilized to safeguard flowers. The effect of soil temperature on pollinator trees should also be considered; while optimal soil temperature supports root growth and photosynthesis, increases due to global warming can cause water stress and affect yield and quality (Fischer *et al.*, 2021). Controlling wind and humidity levels can enhance pollination efficiency (Haokip *et al.*, 2020). Monitoring flowering periods and identifying the most suitable time for pollination can improve fruit set (Haokip *et al.*, 2020).

**Table 2. Honeybee (*Apis mellifera*) colony placement times and required colony numbers per hectare for specific fruit species.**

Fruit crops	Blooming period of the crop	<i>A. mellifera</i> colonies/ha	Time of placement of colonies
Almond	Mid-February to mid-March	5-8	5-10% bloom
Apple	April (7-10 days)	5-8	5% bloom
Apricot	Mid-February to mid March (2-3 weeks)	2-3	5-10% bloom
Avocado	April-May	5-8	10-15% bloom
Cherry	March-April (7-10 days)	2-3	5% bloom
Citrus	March-April	2-3	5-10% bloom
Kiwifruit	March-April	8-9	5-10% bloom
Litchi	March-April	2-3	5-10% bloom
Mango	February	2-3	5-10% bloom
Peach	February-March (3-4 weeks)	1-2	5-10% bloom
Pear	March-April (7-10 days)	5	5% bloom
Persimmon	March-April (2 weeks)	2-3	5-10% bloom
Plum	Mid-February to March (1-2)	2-3	5% bloom

	weeks)		
Strawberry	February-April (2 months)	>15	5-10% bloom

Source: Adapted from Abrol (2012).

Long-term adaptation may involve reassessing the suitability of existing fruit-growing regions based on climate change projections and potentially shifting to areas with more favorable climatic conditions (Ramírez and Kallarackal, 2015). However, such large-scale transitions entail significant economic, social, and ecological challenges.

In summary, comprehensive adaptation strategies are necessary to counter the adverse effects of climate change on the pollination of temperate fruit species. The selection and development of resilient cultivars, effective pollinator management, the conservation and improvement of pollinator habitats, and the reduction of harmful pesticide use, alongside the optimization of orchard practices, are crucial for ensuring sustainable fruit production.

## DISCUSSION AND RECOMMENDATIONS

The evidence presented in this review highlights the multifaceted and escalating impacts of climate change on pollination services, which are of critical importance for temperate fruit cultivation. The advancing phenology observed in temperate fruit species and the alterations in pollinator activity periods disrupt the synchronization of plant-pollinator interactions, thereby posing significant risks to fruit set and ultimate yield (Renner and Zohner, 2018; Polce *et al.*, 2014).

A crucial point for discussion is the marked differences in phenological responses to climate change exhibited by various temperate fruit species and their cultivars (Hegland *et al.*, 2009; Chitu and Paltineanu, 2020). These disparities imply that the risk of phenological mismatch can vary depending on the species, cultivar, and geographical location. For instance, some early-flowering cultivars may coincide with a period when pollinators are not yet sufficiently active, whereas later-flowering cultivars might face different challenges. Therefore, regional-level phenological monitoring and risk assessment form the foundation for effectively determining adaptation strategies (Byers, 2017).

Furthermore, the impacts of climate change on pollinator populations are not confined solely to phenological shifts. Climate change, compounded by other anthropogenic pressures such as habitat loss and fragmentation, pesticide use, and diseases, is leading to declines in overall

pollinator populations and a reduction in species diversity (Goulson *et al.*, 2015; Sánchez-Bayo and Wyckhuys, 2019; Vasiliev and Greenwood, 2021; Olsen *et al.*, 2022). This situation diminishes the reliability of existing pollination services in temperate fruit orchards and can exacerbate the potential effects of phenological mismatch. Reduced pollinator diversity, by leading to the loss of species with differing tolerances to various climatic conditions, can decrease the resilience of pollination services to climate change (Winfree and Kremen, 2009; Bartomeus *et al.*, 2013). However, some species, such as native bees, may buffer the negative impacts of climate warming on honeybee pollination (Rader *et al.*, 2016). The potential decline of traditional pollinators due to climate change and the interactions of species (both native and managed) that could compensate for this decline urgently require further investigation.

Considering future climate scenarios, the projected potential threats to temperate fruit cultivation include irregular and weak flowering due to insufficient winter chilling duration (Luedeling *et al.*, 2009), an increased risk of spring frost damage resulting from early flowering (Chitu and Paltineanu, 2020), and direct adverse effects of extreme temperatures and drought on both plant reproduction and pollinator activity (Scaven and Rafferty, 2013; Ramírez and Kallarackal, 2015). High temperatures (e.g., above 30°C) have been reported to reduce pollen viability and germination in some fruit species (Ramírez and Davenport, 2016). Such temperatures [40-50°C] cause severe damage to plants, including disruption of tissue integrity, protein denaturation, and systemic fertilization failures, leading to dramatic reductions in fruit set and quality (Ramírez and Davenport, 2016). These multifaceted threats necessitate comprehensive and proactive preparedness for the sector.

In light of these findings, it is of paramount importance to take urgent and coordinated measures at stakeholder levels to mitigate the adverse effects of climate change on the pollination of temperate fruit species and to ensure sustainable fruit production in the future.

### **Recommendations for researchers:**

- Long-term, regional, and species-specific monitoring studies should be conducted to determine the phenological responses of various temperate fruit species and cultivars to climate change, and the underlying genetic and physiological mechanisms of these responses (Byers, 2017).

- The phenological responses, population dynamics, and contributions to temperate fruit pollination of important pollinator species (including native and commercial wild bees, beyond honeybees) should be investigated more comprehensively.
- Advanced modeling tools that incorporate geographical and ecological details should be developed for future projections of plant-pollinator phenological mismatch under various climate change scenarios.
- Field-based research and economic analyses should be conducted to evaluate the effectiveness of different adaptation strategies (e.g., new cultivars, pollinator habitat management, cultural practices) on pollination success, fruit set, and yield under climate change conditions.
- The development of low-chilling requirement cultivars is the most suitable solution for addressing the problem of insufficient chilling, and breeding efforts should be focused in this direction (Haokip *et al.*, 2020).

#### **Recommendations for growers:**

- Considering regional climate change trends and phenological forecasts, the selection of cultivars that are more adaptable to changing conditions or are phenologically more flexible should be evaluated (Ramírez and Kallarackal, 2015). Cultivars with low chilling requirements should be preferred (Haokip *et al.*, 2020).
- Practices that enhance biodiversity in orchards (e.g., flowering plant strips, preservation of natural areas) should be encouraged to support local pollinator populations (Scaven and Rafferty, 2013; Sheffield, 2014; Ramírez and Kallarackal, 2018b; Haokip *et al.*, 2020). Polyculture systems and species with broad flowering windows increase ecosystem resilience (Geppert *et al.*, 2024).
- The use of pesticides unsafe for pollinators should be avoided, or applied within the framework of integrated pest management (IPM) principles, using targeted products and timed for periods of low pollinator activity (Goulson *et al.*, 2015; Haokip *et al.*, 2020). Organic farming practices can also enhance efficiency by protecting pollinator populations (Haokip *et al.*, 2020).
- If commercial pollinators are used, the health and vitality of colonies should be regularly monitored and positioned to ensure optimal synchronization with the flowering period (Sheffield, 2014).

- In situations where natural pollination is compromised, the application of managed techniques such as artificial (hand) pollination should be considered to secure fruit set and yield, particularly during periods of low pollinator activity caused by phenological mismatch or adverse weather conditions (Abrol, 2012).
- In regions at risk of insufficient winter chilling, measures aimed at mitigating this risk through cultural practices (e.g., dormancy breaking treatments) or cultivar adaptation should be taken (Fischer *et al.*, 2024). Artificial chilling techniques can also be employed (Luedeling *et al.*, 2011; Haokip *et al.*, 2020).
- Cultural practices such as optimal irrigation and fertilization can improve floral quality, thereby increasing pollinator attraction (Scaven and Rafferty, 2013). Soil temperature management is also important for root health and yield (Fischer *et al.*, 2021). Controlling wind and humidity levels can enhance pollination efficiency (Haokip *et al.*, 2020).

### **Recommendations for policy makers:**

- National and regional agricultural and environmental policies addressing the impacts of climate change on temperate fruit cultivation and the conservation of pollination services should be developed and integrated into existing policies.
- Legal regulations and incentives should be established for land-use planning and habitat conservation programs that support pollinator health and diversity. Incentives and training programs for farmers should promote sustainable practices.
- Financial and infrastructural support for climate change adaptation and pollination research should be increased. Developing countries require programs to evaluate and determine the effects of climate change, pollinators, and trees (Ramírez and Kallarackal, 2018b).
- Education and outreach programs should be provided to farmers, agricultural advisors, and other stakeholders concerning the effects of climate change on pollination, associated risks, and adaptation strategies.

### **CONCLUSION**

This review synthesizes current scientific knowledge regarding the significant impacts of climate change on the phenology and pollination dynamics of temperate fruit species. Rising temperatures advance the flowering times of fruit trees, thereby increasing the risk of

phenological mismatch with pollinator activity periods, which can lead to adverse consequences for fruit set and yield. Declines in pollinator populations further exacerbate these risks. For sustainable temperate fruit cultivation, the adoption of proactive adaptation strategies, such as the selection of climate-resilient cultivars, effective pollinator management, and the conservation of pollinator habitats, is of critical importance. Future research should focus on understanding the regional dynamics of these complex plant-pollinator interactions and the long-term effectiveness of adaptation strategies. Furthermore, international cooperation and awareness-raising efforts are crucial for evaluating the effects of climate change and pollinators and for developing conservation/adaptation strategies. Climate change poses a severe threat to fruit growing by negatively affecting pollinator populations and fruit tree harvests; adaptation and mitigation strategies are necessary to overcome this threat.

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