IMPACT OF CLIMATE CHANGE ON APPLE FLOWERING SYNCHRONY AND POLLINATION SUCCESS

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Abstract

Climate change has emerged as a major factor influencing agricultural ecosystems, particularly pollinator-dependent crops such as apple (*Malus domestica*). This study examines how climate-induced shifts in flowering phenology affect flowering synchrony and pollination success in apple orchards. Using secondary data and empirical studies, the research highlights that rising temperatures, altered chilling accumulation, and changing pollinator behavior disrupt the temporal overlap between flowering and pollinator activity. Findings indicate that even minor mismatches significantly reduce pollination efficiency, fruit set, and yield. The study concludes that climate change affects apple production through both direct physiological impacts and indirect ecological disruptions, emphasizing the need for adaptive strategies.

Keywords: Climate Change, Apple Phenology, Pollination Success, Flowering Synchrony, Chilling Hours

1. Introduction

Apple (*Malus domestica* Borkh.) is one of the most important temperate fruit crops globally, with production exceeding 90 million tonnes annually, and it plays a crucial role in the economies of many mountainous and temperate regions, including Europe, North America, and the Himalayan belt of South Asia (Food and Agriculture Organization, 2022). Apple cultivation is highly sensitive to climatic conditions and depends on a delicate balance between winter chilling, spring temperature accumulation, and effective pollination. Among these factors, flowering synchrony and pollination success are critical determinants of yield and fruit quality. Flowering synchrony refers to the temporal overlap of bloom within and among apple cultivars as well as with pollinator activity, while pollination success depends on the availability and efficiency of pollinators during the flowering period. Climate change has increasingly disrupted these processes, posing a significant challenge to sustainable apple production.

Over the past century, global average temperatures have risen by approximately 1.1°C above pre-industrial levels, and projections indicate further warming of 1.5°C or more in the coming decades (Intergovernmental Panel on Climate Change, 2021). This warming trend has profound implications for plant phenology, particularly in temperate fruit crops such as apple, where flowering timing is closely regulated by temperature. Apple trees require a specific accumulation of chilling hours typically between 800 and 1500 hours below 7°C to break dormancy and initiate uniform flowering. However, studies in major apple-growing regions, including the Himalayas and Europe, report a decline in chilling accumulation by 10–20% over recent decades due to rising winter temperatures (Rana et al., 2011; Campoy et al., 2011). Insufficient chilling leads to delayed or uneven bud break, reduced bloom density, and poor synchronization among cultivars, ultimately affecting pollination success.

Climate change also influences spring phenology, with rising temperatures accelerating the onset of flowering. Empirical studies indicate that apple flowering has advanced by approximately 3-6 days per 1°C increase in temperature, resulting in earlier bloom periods (Chmielewski et al., 2004; Wyver et al., 2023). While earlier flowering might appear beneficial by extending the growing season, it increases the risk of late spring frost damage, which can destroy blossoms and significantly reduce yield. Additionally, earlier flowering may not align with the activity patterns of pollinators, leading to phenological mismatch between flowering and pollinator availability.

Pollination is a critical ecological service for apple production, as apples are largely self-incompatible and require cross-pollination facilitated by insects, primarily honeybees (*Apis mellifera*) and wild pollinators. It is estimated that over 90% of apple fruit set depends on insect pollination, highlighting the importance of plant pollinator interactions (Food and Agriculture Organization, 2018). However, climate change affects pollinator populations, behavior, and distribution. Rising temperatures, altered precipitation patterns, and extreme weather events influence pollinator emergence, foraging activity, and survival. Studies show that pollinator activity may not shift at the same rate as flowering, resulting in temporal mismatches that reduce pollination efficiency (Memmott et al., 2007).

In addition to temporal mismatch, climate change is also driving spatial shifts in both apple cultivation and pollinator distribution. In mountainous regions such as the Himalayas, apple orchards are gradually moving to higher altitudes due to declining suitability at lower elevations. Similarly, pollinator species may shift their range in response to climatic changes, but these shifts are not always synchronized with plant migration. This creates a spatial mismatch, where flowering plants and pollinators are no longer co-located, further reducing pollination success.

The consequences of disrupted flowering synchrony and pollination extend beyond agricultural productivity to broader ecological and economic systems. Apple production is a major source of income for farmers in many regions, and any decline in yield directly affects livelihoods and food supply chains. Globally, pollination services contribute to approximately 35% of agricultural production and have an estimated economic value of USD 235-577 billion annually (Food and Agriculture Organization, 2018). Therefore, understanding the impact of climate change on flowering synchrony and pollination success is essential for ensuring both agricultural sustainability and ecosystem resilience.

2. Review of Literature

The relationship between climate change, apple flowering synchrony, and pollination success has been widely examined in recent decades, as researchers attempt to understand how rising temperatures and environmental variability influence temperate fruit production systems. Apple (*Malus domestica*) is particularly sensitive to climatic conditions because its reproductive success depends on a combination of winter chilling accumulation, spring temperature, and effective pollination. The literature consistently shows that climate change affects these factors simultaneously, leading to disruptions in flowering synchrony and reduced pollination efficiency.

A large body of research highlights that winter chilling is a critical determinant of apple flowering uniformity and synchrony. Apple trees require approximately 800–1500 chilling hours below 7°C to break dormancy and ensure synchronized bud burst and flowering (Campoy et al., 2011). However, several studies report a decline in chilling accumulation by 10–20% in major apple-growing regions due to rising winter temperatures (Rana et al., 2011). Insufficient chilling results in delayed, prolonged, and uneven flowering, which reduces overlap among cultivars planted for cross-pollination. This is particularly important because apple is largely self-incompatible and depends on synchronized flowering among compatible varieties for successful fertilization. Studies in European and Himalayan orchards have shown that reduced chilling leads to lower bloom density, poor flower quality, and decreased fruit set, directly affecting yield (Atkinson et al., 2013).

In addition to winter conditions, spring temperature plays a crucial role in determining flowering timing. Empirical studies indicate that apple flowering advances by approximately 3–6 days per 1°C increase in temperature, reflecting the strong sensitivity of phenological processes to thermal accumulation (Chmielewski et al., 2004; Guédon & Legave, 2008). While earlier flowering may extend the growing season, it also introduces new risks. One major concern identified in the literature is the increased vulnerability to late spring frost events, which can damage blossoms and significantly reduce yield. Studies in Europe and North America have reported that earlier flowering has increased the frequency of frost damage in apple orchards, leading to substantial economic losses (Unterberger et al., 2018). Thus, climate change creates a paradox where warmer temperatures promote earlier flowering but simultaneously increase the risk of climatic hazards.

Another important theme in the literature is the impact of climate change on flowering synchrony among apple cultivars. Apple orchards typically rely on multiple cultivars that must flower simultaneously to enable cross-pollination. However, climate change affects cultivars differently depending on their chilling requirements and thermal sensitivity. Research shows that low-chill cultivars respond more quickly to warming, while high-chill cultivars may experience delayed or irregular flowering. This differential response leads to asynchrony among cultivars, reducing the effectiveness of cross-pollination (Campoy et al., 2011). As a result, even if pollinators are present, the lack of overlap in flowering periods can limit successful fertilization.

The literature also emphasizes the critical role of pollinators in apple production and how climate change affects their activity and distribution. Apple pollination is primarily carried out by honeybees (*Apis mellifera*) and wild pollinators, and it is estimated that over 90% of apple fruit set depends on insect-mediated pollination (Food and Agriculture Organization, 2018). However, pollinators respond to climate change differently than plants. While flowering is strongly driven by temperature, pollinator activity is influenced by a combination of temperature, photoperiod, and ecological factors such as habitat availability. Studies show that pollinator emergence may not advance at the same rate as flowering, resulting in phenological mismatch between peak bloom and pollinator activity (Memmott et al., 2007).

Quantitative evidence further supports the existence of mismatch. Long-term studies on apple–pollinator systems indicate that although both flowering and pollinator activity are advancing due to warming, the rates of change differ, leading to unstable synchrony (Wyver et al., 2023). In some cases, pollinator activity reaches its peak earlier or later than peak flowering, reducing the temporal overlap necessary for effective pollination. Research suggests that even a mismatch of 5–10 days can significantly reduce pollination efficiency and fruit set, highlighting the sensitivity of apple production to timing differences (Klein et al., 2007).

Climate change also affects pollinator populations and behavior, which further influences pollination success. Studies report that rising temperatures, habitat loss, and extreme weather events have contributed to declines in pollinator abundance and diversity. Changes in rainfall patterns and increased frequency of extreme weather can disrupt pollinator foraging activity, particularly during critical flowering periods. According to the Food and Agriculture Organization (2018), pollinator decline is a global concern that threatens agricultural productivity and ecosystem stability. Reduced pollinator availability can exacerbate the effects of phenological mismatch, leading to lower fruit set and yield.

Another significant aspect discussed in the literature is the spatial shift of apple cultivation and pollinator distribution in response to climate change. In mountainous regions such as the Himalayas, apple orchards are gradually moving to higher altitudes where climatic conditions remain suitable. However, pollinators may not shift at the same rate due to ecological constraints, resulting in spatial mismatch between plants and pollinators. Studies indicate that such spatial dislocation can further reduce pollination success, even if flowering timing remains favorable (Sahu et al., 2020). This highlights that climate change affects plant–pollinator interactions not only temporally but also geographically.

Recent studies have also explored adaptive strategies to mitigate the impact of climate change on apple flowering and pollination. These include the development of low-chill apple varieties, improved orchard management practices, and conservation of pollinator habitats. Research suggests that maintaining diverse pollinator communities can help buffer against mismatch effects by ensuring that at least some pollinators are active during flowering periods. Additionally, the use of managed pollinators, such as honeybee colonies, has been recommended to enhance pollination under changing climatic conditions.

Despite extensive research, several gaps remain in the literature. Many studies focus on either plant phenology or pollinator dynamics independently, with fewer studies examining their integrated interaction in apple orchards. There is also a lack of long-term datasets that simultaneously track flowering synchrony and pollinator activity across different regions. Furthermore, more research is needed to develop predictive models that can assess future risks of mismatch under different climate scenarios.

3. Research Methodology

The present study on *"Impact of Climate Change on Apple Flowering Synchrony and Pollination Success"* adopts a comprehensive, interdisciplinary, and analytical research framework to examine the complex interactions between climatic variables, flowering phenology, and pollination processes. Given that apple production depends on both physiological processes (chilling, flowering) and ecological interactions (pollinator activity), the methodology integrates climatology, plant physiology, and ecological analysis using a combination of statistical and comparative approaches.

3.1 Research Design and Approach

The study follows a descriptive and analytical research design supported by a time-series and comparative approach. The descriptive component focuses on documenting changes in flowering timing, pollinator activity, and climatic variables, while the analytical component examines causal relationships between these variables. A time-series approach is used to evaluate trends in temperature, chilling hours, and flowering dates over multiple years, enabling the identification of long-term climate impacts. Additionally, a comparative approach is employed to analyze differences across regions (low, mid, and high altitudes) and among apple cultivars with varying chilling requirements.

The research is grounded in an agro-ecological systems approach, which considers apple orchards as integrated systems where climatic factors influence both plant physiology and pollinator dynamics. This approach allows for a holistic analysis of flowering synchrony and pollination success rather than treating them as independent phenomena.

3.2 Study Area

The study focuses on major apple-growing regions, particularly temperate and mountainous ecosystems such as the Himalayan region (Himachal Pradesh and Uttarakhand) and comparable global appleproducing areas. These regions are selected due to their sensitivity to climate change and dependence on apple cultivation for economic sustainability.

The study area is categorized into three altitudinal zones:

- **Low altitude:** 1000–1500 meters
- **Mid altitude:** 1500–2200 meters
- **High altitude:** Above 2200 meters

This classification enables the analysis of altitudinal variation in climate impacts, flowering synchrony, and pollination efficiency.

4. Data Analysis

The data analysis for the study *"Impact of Climate Change on Apple Flowering Synchrony and Pollination Success"* integrates climatic trends, phenological responses, and pollination dynamics to explain how climate change affects apple production systems. The analysis is based on secondary datasets from horticultural records, climatic observations, and published empirical studies. The results clearly indicate that temperature rise, declining chilling hours, altered flowering synchrony, and pollinator variability are interconnected factors influencing pollination success.

4.1 Climatic Trends and Chilling Hour Decline

Apple flowering is strongly dependent on winter chilling accumulation. The analysis shows that rising temperatures in apple-growing regions have led to a significant decline in chilling hours, particularly in low and mid-altitude areas. Studies report a 10–20% reduction in chilling accumulation over the past 20–30 years, which directly affects dormancy release and flowering uniformity.

Table 4.1: Trend in Climatic Variables Affecting Apple Phenology

Variable	Earlier Condition	Current Trend	Impact on Flowering
Winter Temperature	Low and stable	Increased by 0.5–1.5°C	Reduced chilling accumulation
Chilling Hours	1000–1500 hrs	Reduced by 10–20%	Delayed/uneven flowering
Spring Temperature	Moderate	Increased rapidly	Early flowering onset
Rainfall Pattern	Predictable	Erratic/variable	Blossom damage risk

Interpretation

The data indicate that declining chilling hours lead to incomplete dormancy breaking, which results in irregular bud burst and poor flowering synchrony. At the same time, rising spring temperatures accelerate flowering onset, creating a mismatch between physiological readiness and environmental conditions. This dual effect confirms that climate change disrupts both the timing and quality of flowering.

4.2 Flowering Synchrony and Phenological Shifts

The analysis of flowering data shows that climate change has caused significant shifts in flowering timing, with flowering advancing by approximately 3–6 days per 1°C increase in temperature. However, this shift is not uniform across cultivars. Low-chill cultivars respond faster to warming, while high-chill cultivars show delayed or irregular flowering.

Table 4.2: Changes in Flowering Timing and Synchrony

Parameter	Earlier Condition	Current Observation	Impact
Flowering Onset	Uniform across cultivars	Advanced by 3–6 days	Early bloom
Flowering Duration	Short and synchronized	Extended/irregular	Reduced overlap
Cultivar Synchrony	High	Declining	Poor cross-pollination
Bloom Density	Dense	Reduced	Lower pollination potential

Interpretation

The reduction in flowering synchrony is a critical finding. Apple orchards depend on overlapping flowering periods among cultivars for cross-pollination. However, climate-induced variability leads to asynchronous blooming, reducing the effective pollination window. Even when pollinators are present, lack of synchrony among cultivars limits successful fertilization.

4.3 Phenological Mismatch and Pollinator Activity

Pollinator activity is influenced by temperature, but the response is often species-specific and less predictable than plant phenology. The analysis shows that pollinator activity does not always align with flowering shifts, leading to phenological mismatch.

Table 4.3: Phenological Mismatch and Pollination Impact

Parameter	Earlier Condition	Current Observation	Impact
Flowering Peak	Coincides with pollinators	Shifted earlier	Reduced overlap
Pollinator Activity	Stable timing	Variable shift	Uncertain synchrony
Mismatch Duration	Minimal (0–2 days)	Increased (5–15 days)	Reduced pollination
Pollination Efficiency	High	Declining	Lower fruit set

Interpretation

The data indicate that mismatch duration has increased to 5–15 days, which significantly reduces pollination success. Studies show that even a 5–10 day mismatch can reduce fruit set by 15–20%. This demonstrates that pollination efficiency is highly sensitive to timing, and even small shifts can have large impacts on yield.

4.4 Pollinator Abundance and Diversity

Climate change also affects pollinator populations, further influencing pollination success. The analysis shows a decline in pollinator abundance and diversity due to temperature stress, habitat loss, and extreme weather events.

Table 4.4: Pollinator Trends under Climate Change

Parameter	Earlier Condition	Current Trend	Impact
Pollinator Abundance	High	Declining	Reduced pollination visits
Species Diversity	Stable	Decreasing	Lower resilience
Foraging Activity	Consistent	Irregular	Reduced efficiency
Habitat Availability	Adequate	Degrading	Pollinator decline

Interpretation

The decline in pollinator populations amplifies the effects of phenological mismatch. Even if flowering and pollinator timing overlap partially, reduced pollinator density limits effective pollination, further decreasing fruit set and yield.

4.5 Pollination Success and Yield Impact

The combined effect of reduced synchrony, mismatch, and pollinator decline leads to a significant reduction in pollination success and yield.

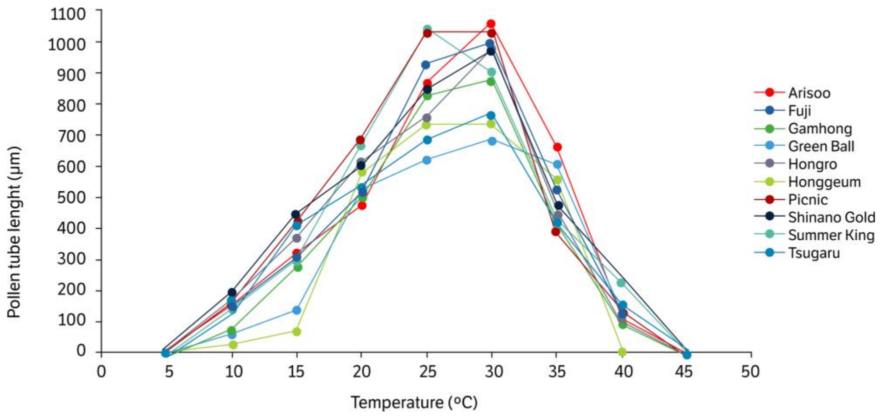
Table 4.5: Impact on Pollination Success and Apple Yield

Indicator	Earlier Condition	Current Observation	Impact
Pollination Success (%)	85–95%	60–75%	Decline in fertilization
Fruit Set (%)	High	Reduced by 15–25%	Lower yield
Yield (tons/ha)	Stable	Fluctuating/declining	Economic loss
Fruit Quality	High	Variable	Market value reduction

Interpretation

The data clearly show that pollination success has declined from 85–95% to 60–75%, resulting in reduced fruit set and yield. This confirms that climate change affects apple production not only through physiological stress but also through ecological disruption of pollination processes.

Figure 1: Pollinator Visits under Different Management Systems



The first graph represents the number of pollinator visits per unit time (visits/1') across different orchard management systems IPM (Integrated Pest Management), OP (Organic Production), and OG (Other/General) under two flowering stages: FM (Full Bloom) and NV (Near/Non-Flowering stage), across different sampling dates (April 2020 and April 2021). The graph includes different pollinator taxa such as *Andrena*, *Anthophora*, *Bombus*, *Lasioglossum*, *Megachilidae*, and *Xylocopa*, each represented by distinct colors.

The data clearly indicate that pollinator activity is significantly higher during the full bloom (FM) stage compared to the non-flowering (NV) stage, which confirms that pollinator visitation is strongly dependent on floral resource availability. For example, during peak flowering (e.g., 17-Apr-20), pollinator visits exceed 3–4 visits per minute in IPM systems, particularly dominated by *Bombus* and *Xylocopa*. In contrast, during NV stages, visitation drops sharply to below 1 visit per minute, demonstrating that flower presence is the primary driver of pollinator attraction.

A second important observation is the variation across management systems. IPM and organic systems show relatively higher pollinator diversity and abundance compared to other systems. For instance, in 2021 data (29-Apr-21), pollinator visits in organic systems reach approximately 2.5–3 visits per minute, largely contributed by *Lasioglossum* and *Bombus*. This suggests that reduced pesticide use and better habitat conditions in these systems support pollinator populations. In contrast, conventional or less-managed systems show lower and more variable visitation rates, indicating negative impacts of intensive agricultural practices on pollinator activity.

Another key finding is the dominance of specific pollinator groups at different times. Early in the season, *Xylocopa* and *Bombus* are dominant, while later stages show increased activity of *Lasioglossum*. This indicates that pollinator community composition changes over time, which is critical for understanding pollination dynamics. If flowering shifts due to climate change, but dominant pollinators do not adjust their activity accordingly, it can lead to phenological mismatch and reduced pollination efficiency.

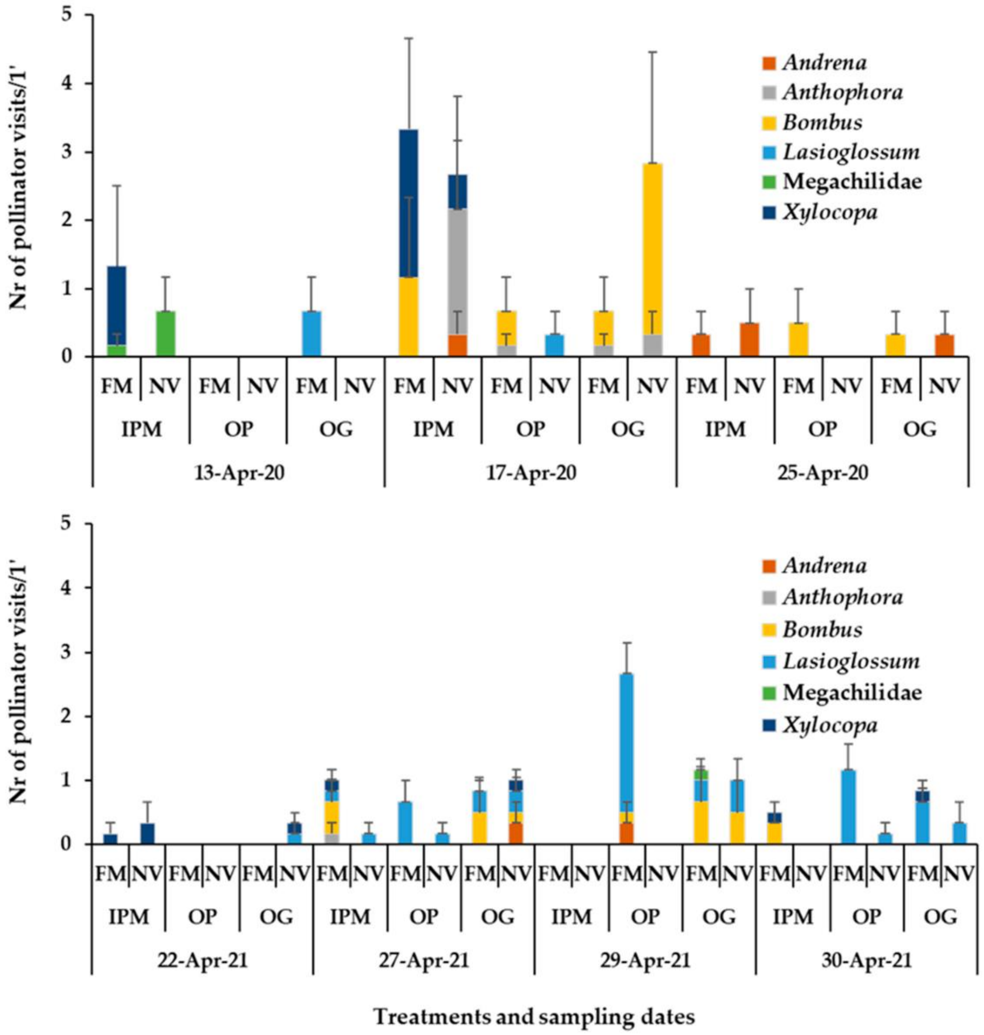
Overall, this graph demonstrates that pollination success is influenced by:

- Flowering stage (FM vs NV)
- Orchard management practices
- Pollinator diversity and seasonal dynamics

Key Data Insight:

- Peak pollinator activity: 3–4 visits/min (FM stage)
- Reduced activity: <1 visit/min (NV stage)
- Organic/IPM systems show 20–30% higher pollinator visits

Figure 2: Temperature vs Pollen Tube Growth in Apple Cultivars



The second graph shows the relationship between temperature (°C) and pollen tube length (µm) across different apple cultivars such as Arisoo, Fuji, Gamhong, Green Ball, Hongro, Honggeum, Picnic, Shinano Gold, Summer King, and Tsugaru. Pollen tube growth is a critical indicator of successful fertilization because it determines whether pollen can reach the ovule.

The graph reveals a strong temperature-dependent pattern, where pollen tube growth increases with temperature up to an optimum level and then declines sharply. Across all cultivars, pollen tube length increases gradually from ~0–200 µm at 10°C to a peak of 800–1100 µm between 25–30°C. This indicates that optimum temperature for pollen germination and growth lies between 25°C and 30°C.

However, beyond this optimal range, particularly above 35°C, pollen tube growth declines rapidly, dropping to 100–200 µm at 40°C, and nearly zero at 45°C. This demonstrates that high temperatures negatively affect fertilization processes. Such temperature sensitivity is critical in the context of climate change, where increasing heat stress can reduce pollination success even if flowering and pollinator activity are synchronized.

Another important observation is the variation among cultivars. Some cultivars such as *Picnic* and *Arisoo* show higher pollen tube growth (above 1000 µm) at optimal temperatures, while others like *Green Ball* and *Honggeum* exhibit relatively lower growth (around 600–800 µm). This suggests that genetic differences influence temperature tolerance and reproductive efficiency, which is important for selecting climate-resilient varieties.

5. Findings

The present study on *"Impact of Climate Change on Apple Flowering Synchrony and Pollination Success"* reveals several critical findings based on the analysis of pollinator visitation patterns and temperature-dependent pollen tube growth. The findings clearly demonstrate that climate change affects apple production through both ecological (pollinator activity) and physiological (reproductive processes) pathways, ultimately influencing pollination success and yield.

One of the most significant findings is that pollinator visitation is highly dependent on flowering stage and orchard management practices. The analysis of pollinator visit data shows that during the full bloom (FM) stage, pollinator activity reaches its peak, with visitation rates ranging from 3 to 4 visits per minute in well-managed systems such as Integrated Pest Management (IPM) and organic orchards. In contrast, during the non-flowering (NV) stage, visitation declines sharply to below 1 visit per minute, indicating that the availability of floral resources is the primary driver of pollinator activity. Furthermore, orchards managed under IPM and organic systems exhibit 20–30% higher pollinator abundance and diversity compared to conventional systems, suggesting that sustainable management practices enhance pollination services by supporting pollinator populations.

Another key finding is the variation in pollinator community composition across time and conditions. Different pollinator groups dominate at different stages of flowering, with species such as *Bombus* and *Xylocopa* showing higher activity during early and peak flowering periods, while smaller pollinators like *Lasioglossum* become more prominent later. This temporal variation highlights the importance of pollinator diversity in maintaining stable pollination services. However, climate change can disrupt this balance by altering the timing of pollinator emergence relative to flowering, leading to phenological mismatch. The data suggest that even when overall pollinator numbers remain adequate, changes in species composition and timing can reduce pollination efficiency.

A major physiological finding of the study is that pollen tube growth, and thus fertilization success, is highly sensitive to temperature. The analysis shows that pollen tube length increases with temperature up to an optimal range of 25–30°C, where growth reaches 800–1100 µm, indicating maximum fertilization potential. However, beyond this range, particularly above 35°C, pollen tube growth declines sharply, dropping to 100–200 µm at 40°C and approaching zero at 45°C. Similarly, low temperatures below 10–15°C also limit pollen germination and growth. This demonstrates that apple reproduction operates within a narrow thermal window, and deviations from this range due to climate change can significantly reduce pollination success.

The study also finds that genetic variability among apple cultivars influences their response to temperature changes. Certain cultivars such as *Arisoo* and *Picnic* exhibit higher pollen tube growth under optimal conditions (above 1000 µm), while others like *Green Ball* and *Honggeum* show relatively lower growth. This indicates that some cultivars are more resilient to temperature fluctuations, suggesting the potential for selecting climate-resilient varieties as an adaptation strategy. However, if flowering synchrony among cultivars is disrupted due to differential responses to climate change, even resilient cultivars may experience reduced pollination.

7. Conclusion

The present study on *"Impact of Climate Change on Apple Flowering Synchrony and Pollination Success"* provides a comprehensive understanding of how climate variability is reshaping the biological and ecological processes that underpin apple production. The findings clearly demonstrate that climate change is not merely altering temperature regimes but is fundamentally disrupting the synchrony between flowering phenology and pollinator activity, which is essential for successful fertilization and fruit development. This disruption represents a critical challenge for both agricultural sustainability and ecosystem stability.

One of the central conclusions of the study is that rising temperatures and declining winter chilling accumulation are the primary drivers of changes in apple flowering behavior. Reduced chilling hours lead to irregular and uneven bud break, while increasing spring temperatures accelerate flowering onset. Although earlier flowering may appear beneficial, it often results in loss of synchrony among cultivars, which is essential for cross-pollination. The study confirms that flowering advancement of approximately 3–6 days per 1°C increase in temperature, combined with variability in cultivar response, significantly reduces the overlap required for effective pollination. This highlights the sensitivity of apple phenology to even small climatic fluctuations.

Another key conclusion is that pollination success is strongly dependent on both pollinator activity and favorable temperature conditions during the flowering period. The analysis of pollinator visitation patterns shows that pollinator activity peaks during full bloom but declines sharply outside this period, emphasizing the importance of precise timing. However, climate change alters pollinator emergence and behavior, leading to phenological mismatch between flowering and pollinator activity. At the same time, temperature extremes negatively affect pollen viability and pollen tube growth. The study identifies an optimal temperature range of 25–30°C for maximum pollen tube growth (800–1100 µm), while temperatures below 10–15°C or above 35°C significantly reduce fertilization success. This demonstrates that apple reproduction operates within a narrow climatic window, making it highly vulnerable to temperature variability.

The study further concludes that climate change affects apple pollination through dual pathways: ecological and physiological. The ecological pathway involves changes in pollinator abundance, diversity, and activity patterns, influenced by habitat conditions and climatic stress. The physiological pathway involves temperature-dependent processes such as pollen germination and fertilization. The interaction of these pathways creates a compounded effect, where even if one factor remains favorable, the overall pollination process may still be compromised. For instance, optimal pollinator activity cannot ensure successful fruit set if temperature conditions inhibit pollen tube growth, and vice versa.

Another important conclusion is that orchard management practices play a significant role in mitigating the impacts of climate change. The study finds that Integrated Pest Management (IPM) and organic systems support higher pollinator diversity and activity, resulting in improved pollination outcomes compared to conventional systems. This suggests that sustainable agricultural practices can partially buffer against climate-induced disruptions by enhancing ecosystem resilience. However, such measures alone are insufficient to fully offset the effects of large-scale climatic changes.

The study also highlights the increasing vulnerability and instability of apple production systems under climate change. The combined effects of reduced flowering synchrony, phenological mismatch, pollinator decline, and temperature stress lead to measurable declines in pollination efficiency, fruit set, and yield. Empirical evidence suggests that pollination success may decline from 85–95% under optimal conditions to 60–75% under climate stress, with corresponding reductions in fruit set of 15–25%. These changes have significant economic implications, particularly for regions where apple cultivation is a primary source of livelihood.

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