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Impact of Climate Change (CC) on Guava (*Psidium guajava* L.) Phenology, Yield and Commercial Fruit Quality; Prospective Policy

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Bilal Ahmed Awan
Plant Tissue Culture Cell, Institute of Horticultural Sciences, University of Agriculture Faisalabad Pakistan
bilal.awan@uaf.edu.pk

Muhammad Usman
Plant Tissue Culture Cell, Institute of Horticultural Sciences, University of Agriculture Faisalabad Pakistan
m.usman@uaf.edu.pk

Bilquees Fatima
Plant Tissue Culture Cell, Institute of Horticultural Sciences, University of Agriculture Faisalabad Pakistan
dr.fatimausman@uaf.edu.pk

Hasham Feroz Ghuman
Centre of Agricultural Biochemistry and Biotechnology (CABB), University of Agriculture Faisalabad Pakistan
Hasham.feroz@uaf.edu.pk

Bushra Rashid
Centre of Excellence in Molecular Biology (CEMB), University of the Punjab, Lahore, Pakistan
bushra.cemb@pu.edu.pk

Faisal Saeed Awan
Centre of Agricultural Biochemistry and Biotechnology (CABB), University of Agriculture Faisalabad Pakistan.
Faisal.saeed@uaf.edu.pk

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Abstract: *It has been observed that the climate is changing from last few couple of years. One of the many negative consequences of climate change is the alteration of the natural vegetation and environment. Phenology, or the shifting timing of plant growth activity, is one of the most well-documented consequences of climate change. Climate change is causing changes in the length of the vegetative and reproductive phases. By shortening the vegetative period, warmer temperatures often reduced the number of days needed for flowering in the majority of fruit crops. Guava (Psidium guajava L.) commercially 3rd fruit crop of significant economic importance in Pakistan and high nutritional potential, yet its production faces severe challenges during last two decades due to climate change overall globally and more frequently in South East Asian (SEA) countries. This comprehensive effort highlight and examines the climate change (CC) impact on Guava phen-phases, crop improvement and overall fruit quality parameters, highlighting disruptions caused by rising temperatures, altered precipitation patterns, and increased frequency of extreme weather events such as long summer season span, droughts and heavy rainfall during monsoon weather. These changes affect critical physiological processes, including flowering, fruit setting, fruit growth and maturation leading to irregular bearing, reduced yields, and compromised fruit quality such as, size, color and sweetness. Climate-induced biotic stressors exacerbate pest and disease pressures, further threatening commercial production. adaptation and mitigation precision horticulture strategies, including improved irrigation systems, canopy management techniques during high density plantation and efficient use of micronutrients like zinc and boron, are practical solutions to enhance resilience. the paper also explores future perspectives, emphasizing precision horticulture and supportive policy frameworks to ensure sustainable guava production. by integrating advanced technologies, resilient cultivars and innovative pomological* *practices, this study underscores potential to mitigate impact of climate change (CC) for secure guava production.*

Keywords: *Guava, Climate Change, Phenology, Fruit Setting, Mitigation Strategies.*

Introduction

Throughout Earth's history, the planet's climate has experienced several changes, from ice ages to warm eras. Agriculture was one of the first industries to be examined the climate change (CC) effects because of its vital role in human existence (Adams et al., 1990; Ahmed et al., 2025; Scorzini et al., 2026). Many crop models and evaluation strategies have been created recently for important horticultural crops, such as fruit crops (Chmielewski et al., 2004; Chawla et al., 2011; Fischer et al., 2016; Haokip et al., 2020; Karagatiya et al., 2023), offering predictions related to crop yield.

The capacity of reflected infrared radiation in the atmosphere is increased by increased greenhouse gas emissions, which eventually raises the temperature of the surface-troposphere system. According to NASA data from October 2020, atmospheric CO_2 concentrations just reached a record of 415ppm after quickly increasing to 400ppm in 2014. The Intergovernmental Panel on Climate Change (IPCC) found that between 1906 and 2005, the global air temperature rose by 0.74°C (Donato et al., 2014). An increase of 0.5°C to 1.2°C by 2020, 0.88 to 3.16°C by 2050, and 1.56 to 5.44°C by 2080 is predicted (Scorzini et al., 2026).

According to projections, the global temperature might rise by up to 6°C by the year 2100, and the CO_2 concentration could rise by 550 to 850 parts per million during that same time. The average worldwide air temperature may increase by 1.4°C to 6.4°C by the end of this century. Climate change (CC) is undoubtedly the biggest issue facing the commercial fruit sector today and will require immediate attention in the years to come. The average worldwide air temperature may increase by 1.4°C to 6.4°C by the end of this century (IPCC 2014a; Ahmed et al., 2026).

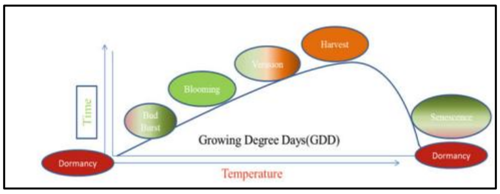

Fig. 1 Thermal time model for growth of perennial fruit crops

Variations in air temperature were noticeable, with typical viticulture zones in various regions of Europe experiencing a rise of 2 to 5°C (Christensen et al. 2007). Climate projections for the 21st century indicate that the average global temperature will increase in a range of ways, from stabilizing at 1.5°C during the current reference period to increasing by almost 4°C (IPCC 2014b). The emission of greenhouse gases, among which CO_2 is more significant in terms of both volume and impact, has been the main driver of the temperature increase (IPCC 2014b). From 280/μL L^{-1} (preindustrial) to above 400/μL L^{-1} in 2016, atmospheric CO_2 levels are expected to rise rapidly to 421–936/μL L^{-1} by the end of the century (Meinshausen et al. 2011). Rainfall has also decreased in important viticultural regions, particularly in Southern Europe (IPCC 2014a; Christensen et al., 2007), and it is anticipated that this decline will persist in the future (Assad et al., 2004). Extreme droughts, floods, and heatwaves are expected to occur more frequently as temperatures rise. Climate change has three different effects on agriculture: direct, indirect, and socioeconomic (Kim et al., 2009).

According to the IPCC SRES-A2 scenario, temperatures are predicted to rise by 3.4°C and CO2 concentrations to reach 1250 ppm by 2095. This might be followed by more extreme weather events and climate variability (Ashraf et al., 2025). New problems including urbanization, water scarcity, soil and water contamination, and global climate change make this complex scenario worse (Pachauri et al., 2007; Kumar et al., 2019). When combined with higher temperatures, less precipitation may result in less irrigation and more evapotranspiration, which might put many crops under water stress (Datta et al., 2013; Yadav et al., 2023).

Guava (*Psidium guajava* L.) is an important crop having both commercial and nutritional significance throughout the tropics and subtropics. Moreover, it is the third most important fruit crop in Pakistan. It is the greatest choice in terms of taste and additional nutritional benefits (Riaz et al., 2025; Usman et al., 2020), as high demand in both local and international markets (Ahmad et al., 2018; Antwi-Boasiako et al., 2024). Fresh Guava and its value-added items are exported by farmers, who profit greatly from fruit products. Guava is therefore an important crop that offers them two cropping patterns annually and huge socioeconomic benefits (Normand et al., 2015; Usman et al., 2021).

Timely blossoming and maximum fruiting of guava trees, which are essential for yield, can be hampered by shifting weather patterns like heat and rain. Low temperatures have been found to be crucial for guava flowering in subtropical environments. But other stressors, including a lack of water, might negatively impact fruit set and retention (Table. 1) (Luo et al., 2019). Climate change may result in phenological mismatches, which will impact flowering and fruiting at irregular periods and increase their susceptibility to pests and diseases. Unfavorable weather patterns might lead to less consistent fruit quality and maturity during harvest, creating additional difficulties for market delivery and customer satisfaction (Boudon et al., 2020).

It is anticipated that the vegetative and reproductive growth of guava trees will be impacted by increases in atmospheric carbon dioxide (CO_2), soil salinity, and reduced and erratic rainfall (Normand et al., 2015; Jan et al., 2025). Difficulties during dry and rainy spells can be overcome by better cultivation techniques and nutrient management, such as applying zinc and boron to the soil together. Guava tree productivity and physiological quality responses can be somewhat improved by such practices.

Additionally, they improve fruit quality, retention and set (Ahmad et al., 2018). Additionally, creating a guava crop model through study can help comprehend these altering effects on guava phenology and find ways to adjust commercial guava production to changing climate scenarios (Normand et al., 2015). Guava is a significant crop, but its stability and production in the face of climate change will depend on a few focused agricultural measures as well as our growing knowledge through research.

Climate Change (CC) Impact on Guava Phenology

Climate change has an impact on the guava's (*Psidium guajava* L.) blooming time, fruit set, and irregular bearing. Rising temperatures, altered precipitation patterns, and a rise in the frequency of extreme weather events are all effects of climate change on guava production (Normand et al., 2015). Guava flowering is influenced by two environmental factors: temperature and humidity. Timing of pheno-indicators can be disrupted by climatic changes, leading to variations in flowering. The intricate process of guava flowering depends on a number of variables, including water availability and temperature. While the age of the final flush of growth is crucial in tropical climates, low temperatures have a significant effect in inducing flowering in subtropical climates (Luo et al., 2019; Jan et al., 2025).

If temperatures keep increasing across the globe, then low-temperature cues that enable flowering may decline. As a result of flowering could delay or disrupt (Khalifa and Abobatta, 2023; Luo et al., 2019). The changes in climate may affect the availability and balance of resources necessary for fruit set such as, non-structural carbohydrates. Guava's starch and sugar contents are directly influenced by its photosynthesis and starch distribution. Changes in climate can alter the amount of carbohydrates available for trees, then affects fruit set and may lead to a reduction in fruit Guava trees are known for periodic flowering and irregular bearing, which makes it worse by climate vagaries, adopting a regional product approach (Jan et al., 2025).

By increasing temperatures and rainfall variability, the phenological disparities can happen. For example, flowering and fruiting may not coincide, which causes variability in fruit production from season to season as shown in (Table. 1) (Normand *et al.*, 2015). Furthermore, stress from extreme climate events like drought and heavy rain prevent adversely impact the health and productivity of the trees (Khalifa and Abobatta, 2023; Jan et al., 2025). Adaptive measures such as breeding for climate-resilient varieties and adjustment in cultural practices are important to mitigate them. You may choose the cultivars that are a good fit for climatic stresses and specify agricultural practices to improve water and soil management (Khalifa and Abobatta, 2023). Long-term strategies, on the other hand, concentrate on better understanding and predicting the phenological occurrences that are altered by climate change. Improving farm management as a buffer against variability would be one of the more workable and immediate answers (Yadav et al., 2023).

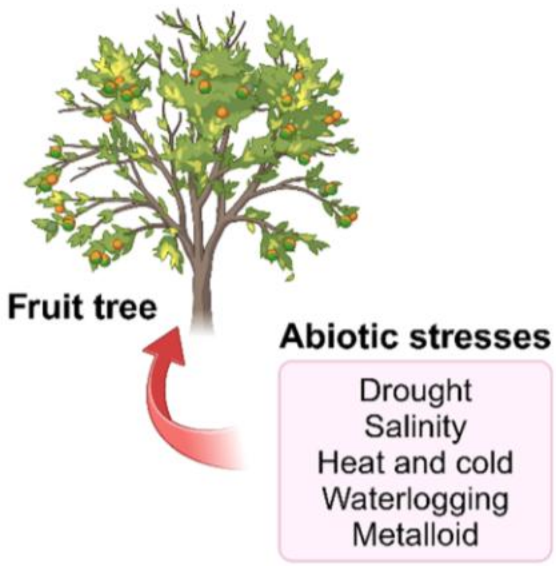

Fig. 2 Abiotic-Stress Effects on Guava Fruit Production

Table 1. Climate change (CC) Impacts on Guava Phenology, Yield and Fruit Quality

Sr. No.	Chronological research work on guava	References
1.	Long Short-Term Memory Model for Guava Yield Prediction Using Harris Hawks Optimization	Khedr et al., 2026
2.	Integrated Nutrient Management Techniques Boost Fruit Yield and Quality in a Sustainable Guava (*Psidium guajava* L.) System of Production	Nodal et al., 2026

3.	Development of Nondestructive Technology for Guava Ripeness Assessment (*Psidium guajava* L.)	Kundu et al., 2026
4.	Effects of Branch Bending on the Production and Fruit Quality of Different Guavas (*Psidium guajava* L.) Different Types	Kumar et al., 2025
5.	Pruning practices affect guava flowering, fruiting, yield, and fruit biochemical characteristics in subtropical climates.	Gomasta et al., 2024
6.	Flower regulation in guava and pomegranate	Sachin et al., 2024
7.	Effective guava cultivar clonal multiplication using tiny softwood cuttings	Awan et al., 2024
8.	Various guava genotypes' flowering, fruiting patterns, and nutritional value	Bose, 2022
9.	The morphological, physiological, biochemical, and molecular responses of guava (*Psidium guajava* L.) cultivars to drought stress	Usman et al., 2022
10.	Seasonal and genetic variations in guava fruit quality and their breeding consequences	Usman et al., 2021
11.	Research on the "Crystal" guava's (*Psidium guajava* L.) flowering and fruiting cycles in three distinct Indonesian sites	Widyastuti et al., 2019
12.	Physiological research on guava tree fruits and flowering	Singer et al., 2017
13.	Intercropping: A strategy to lower fruit drop and enhance guava fruit quality	Singh et al., 2016
14.	Pruning in guava (*Psidium guajava* L.) and assessing the flowering phenology that results using a modified BBCH scale	Singh et al., 2015
15.	Effects of pruning duration and intensity on guava production, quality, flowering, and vegetative growth	Adhikari et al., 2015

16.	Studies on how different pre-harvest methods affect the development and quality of guava fruit	Ali et al., 2014
17.	Defoliation and de-flowering have an impact on the fruit quality of guava (*Psidium guajava* L.) cv. Gola	Khan et al., 2013
18.	Guava CVs. fruiting, yield, and fruit quality as influenced by N, P, and K Pant Prabhat	Kumar et al., 2008
19.	Fruit quality of guavas (*Psidium guajava* L.) in relation to the date of pruning	Singh and Singh, 2001
20.	New guava variety development, blooming, and fruiting patterns	Menzel and Paxton, 1986

Climate change (CC) Impact on Guava Fruit Quality:

Common bushy fruit plant known as guava (*Psidium guajava* L.) is grown in Pakistan and other tropical and subtropical areas of the world. A highly nutraceutical fruit crop, guavas are high in pectin, carotenoids, calcium, vitamin A, and ascorbic acid (three to five times more than citrus) (Usman et al., 2022; Usman et al., 2020). Pakistan now produces 0.79 million tons of fresh guava on 53.85 thousand hectares of land (Fruit, Vegetables and Condiments Statistics of Pakistan, 2023-24). After citrus and mango, guava is the third most popular fruit crop in Pakistan. Despite rising fruit output and guava yield per hectare (8 tons/ha to 14.5 tons/ha), Pakistan is currently the world's fourth-largest guava grower, after China, Indonesia, and India. Improved planting density, cultural methods, and varietal shifts, such as Chinese Gola, may be responsible for the increased yield and productivity. Other factors affecting yield and quality include seedling-based industry, lack of certified nursery (Riaz et al., 2025; Awan et al., 2024).

Fruit crops and climate change (CC) are related because global climate change is primarily responsible for many of the factors that have a detrimental effect on commercial production. Rising temperatures, drought or water stress, changing climate zones, erratic rainfall patterns, and insect pest outbreaks are the primary causes of climate change. Fruit crops are expected to be more affected by climate change than perennials since short-duration crops are frequently better able to adapt. Among the ways that climate change affects fruit crops at different phases of growth and development are fruit sunburn, inadequate pollination, delayed ripening, reduced color development, low sugar content, poor fruit quality and set, and decreased fruit yield. The constantly changing climate has a significant impact on perennial crops in the agriculture and horticultural industries, particularly the fruit business. In 2024, Punjab province provided 66% of mangoes, 34% of dates, 82% of guavas, and more than 90% of citrus fruits to the country's overall fruit production due to the hot months of May and June being followed by substantial rainfall in July and August (www.agripunjab.gov.pk).

Guava's size, color, sweetness, and postharvest quality are all impacted by climate change for a variety of reasons. Variations in temperature, light, and water availability have a major role in determining these fruit characteristics. Guavas develop to a size that is mostly dependent on the resources available to them, namely water and nutrients. Water stress will result from rising temperatures and unpredictable rainfall due to climate change. Fruit size and general quality characteristics in relation to the environment will be affected. (Table. 2).

Furthermore, as seen in Figure 2, higher temperatures may accelerate growth processes, leading to smaller fruit (Antwi Boasiako et al., 2024; Léchaudel and Joas, 2007; Jan et al., 2025). Fruit Temperature and light have an impact on color development. Fruits may have uneven coloring due to changes in these elements brought on by climate change. Higher temperatures may increase the activity of the enzymes that produce pigments, which could result in improved color but also early ripening and other issues (Yadav et al., 2023).

Guava fruit's flavor is mostly determined by how sugars are produced and stored as the fruit ripens. Temperature increases in particular have an impact on the metabolism of carbohydrates, which in turn affects sweetness (Datir and Regan, 2022; Romero et al., 2021). A certain amount of sugar buildup may be increased by warmer temperatures, but too much heat may impede metabolic activities. Physiological issues may have an impact on the quality of picked, ripe fruit. They are brought on by seasonal environmental stress. Fruit appearance, texture, and flavor can be negatively impacted by storage conditions such as damage and uneven ripening. Climate conditions have been stressing harvested fruit, which may increase post-harvest losses and shorten their shelf life, necessitating the use of cutting-edge postharvest equipment (Bambalele et al., 2021; Ullah et al., 2024).

Climate change (CC) Impact on Guava yield

One of the major fruits mostly susceptible to climate change commercial guava (*Psidium guajava* L.), Climate Change may have detrimental effects on the fruit's physiological and developmental processes. Guava yield is decreased in the following ways by rising temperatures, changing rainfall patterns and drought conditions. Higher temperatures during flowering fruit set and fruit growth may have a detrimental effect on commercial fruit output. Fruit and blossoms may drop as a result of this extreme heat stress, significantly reducing yield. Additionally, it can change the fruit's quality, affecting its nutritional content, texture, and flavor (Antwi-Boasiako et al., 2024; Normand et al., 2015; Jan et al., 2025).

Guava trees suffer from drought and water constraint because they require a specific amount of water during their growth cycle. Droughts, which are occurring more frequently due to climate change, can cause water stress. The lower fruit production is due to less photosynthesis and vegetative growth. because it increases the chance of fruit drop and decreases the overall fruit set. An inadequate water supply during the flowering and fruit-setting stages is especially harmful (Normand et al., 2015).

Insufficient rainfall hinders the uptake of nutrients, resulting in water deficiencies that can lead to stressful conditions that reduce fruit output and quality. Mango trees depend on timely and balanced rainfall, which is becoming more erratic due to climate change (Antwi-Boasiako et al., 2024; Normand et al., 2015). Climate factors like temperature and precipitation have an impact on the photosynthesis and nutrient uptake processes of guava trees during active growth periods. Heat and water stress can reduce chlorophyll efficiency and content. As a result, atmospheric photosynthetic processes may become less efficient. Consequently, less energy is generated, which limits fruit production and growth and reduces yield overall (Normand et al., 2015; Jan et al., 2025).

Future Perspectives

Tools like precision horticulture, climate-smart techniques, and legislative actions may help mitigate the harmful effects of climate change on guava production. Together, they improve guava orcharding's sustainability, resilience, and productivity. In order to effectively analyze Horticultural operations, precision horticulture uses mobile platforms, data analysis, remote sensing, and more. These days, farms use smart technology, which are gadgets that give farmers the quick information they require. Precision horticulture, which includes site-specific nutrient management, precise water management, and plant health monitoring using nano-biosensors that can identify biotic and abiotic challenges before they negatively impact production, used for the commercial guava production (Miguel-Rojas and Pérez-De Luque, 2023).

Climate-Smart Horticulture (CSH) refers to sustainable farming methods that boost resilience, reduce emissions, and increase productivity. Crop diversification, conservation agriculture, and the use of agroforestry are among techniques that guarantee consistent yields and improve resilience. Strategies for CSH have been devised, according to Safdar et al. (2024) and Bhanuwanti et al. (2024). For example, guava varieties that are drought and disease resistant were created. Enhancing soil fertility and irrigation effectiveness are two more examples. In addition to increasing mango crop output, it helps lower hazards associated with climate change.

Conclusion

Climate change may have a major effect on guava trees (CC). Climate change has made guava trees more vulnerable to environmental stressors such as drought, intense weather, increased temperatures, and erratic rainfall patterns. Changes in temperature and precipitation can interfere with the growth and fruiting cycles of guava trees. This could have an impact on the phenology, yield, and quality of the fruit. Rising temperatures and more frequent heatwaves may make it more difficult for trees to produce food and carry out other growth phases. Despite the shifting climate, productivity must be maintained, adjusting measures should be used in response to temperature increases. Water scarcity and soil salt buildup due to climate change are exacerbating an already dire scenario. Socioeconomic issues are also becoming more prevalent. Guava quality and productivity are also being impacted. Development of a guava crop model and modifications to cultural practices may offer crucial information for adaptation strategy. The sustainability of guava production and the consequences of climate change can also be addressed by research initiatives on AI-assisted sustainable fruit farming and new IoT technologies.

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