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Impacts of Climate Change on the Agronomic Performance, Phenology, Yield, and Fruit Quality of *Mangifera indica* L.

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ABSTRACT

Mango (*Mangifera indica* L.), a key tropical fruit, is increasingly vulnerable to the impacts of climate change, which poses significant threats to its production, quality, and yield. This review investigates the effects of climate-induced changes, including rising temperatures, erratic rainfall, and extreme weather events, on mango phenology, agronomic performance, and fruit quality. Temperature fluctuations have been found to disrupt flowering, fruit set, and development, while increased humidity and rainfall contribute to the proliferation of pests and diseases, such as anthracnose, compromising fruit quality. Furthermore, climate change leads to water stress, which affects tree growth, fruit size, and overall yield. The review explores adaptation strategies, including genetic improvement through breeding

programs, efficient water management, integrated pest management, and agroforestry practices, as means to mitigate these challenges. By highlighting gaps in current research, such as the need for cultivar-specific responses to climate variability and the importance of region-specific adaptation strategies, this study aims to provide insights into maintaining mango production under changing climatic conditions. Sustainable strategies are critical to ensuring the resilience and economic viability of mango farming worldwide.

Keywords: Climate Change, Mango, Agronomic Performance, Phenology, Yield, Fruit Quality, Adaptation Strategies

1. Introduction

Mango (*Mangifera indica* L.), known as the "King of Fruits," holds significant cultural, economic, and nutritional importance in tropical and subtropical regions around the world. Cultivated across more than 100 countries, mangoes are an essential fruit in the agricultural sector. However, climate change, characterized by rising temperatures, altered precipitation patterns, and increased frequency of extreme weather events, is posing severe challenges to mango production. As one of the most climate-sensitive crops, the impacts of climate change on mango growth, yield, fruit quality, and overall productivity have become a pressing concern for researchers and farmers alike (Singh et al., 2020). Climate change has already altered the timing of mango flowering, fruit set, and ripening, making it necessary to develop effective strategies to safeguard mango production.

The ongoing climate changes have had significant consequences on mango phenology, agronomic performance, and fruit quality. Temperature shifts have influenced the timing of mango flowering, with many regions observing earlier flowering due to rising temperatures. However, these changes have resulted in uneven fruit set and poor fruit development due to excessive heat during critical growth periods (Kushwaha, 2025). Additionally, altered rainfall patterns and increased humidity are contributing to the spread of pests and diseases, such as anthracnose, which further compromise fruit quality and yield (Gupta et al., 2021). Furthermore, the increased frequency of extreme weather events, such as cyclones, storms, and droughts, exacerbates these challenges, leading to substantial economic losses in mango production, particularly in countries like India, Peru, and Nigeria,

where mango farming is a primary source of income (Aragón et al., 2019).

The vulnerability of mango cultivation to climate change is primarily due to its sensitivity to environmental stressors, such as temperature fluctuations and water stress. Mango trees require a specific temperature range for optimal flowering and fruit development. Variations outside this range may hinder pollination and fruit growth, leading to reduced productivity and compromised fruit quality (Sharma et al., 2025). Additionally, water stress due to increased evaporation and decreased rainfall during the growing season poses a significant threat to mango production. Mango trees are highly susceptible to water scarcity, which can lead to stunted growth, smaller fruit size, and lower yields (Halder, 2024).

Given the increasing challenges posed by climate change, it is crucial to explore effective adaptation strategies that can help mitigate these impacts on mango production. Adaptation strategies may include genetic improvements through breeding programs to develop heat- and drought-resistant mango varieties, efficient water management techniques such as drip irrigation and rainwater harvesting, integrated pest management (IPM) systems, and agroforestry practices to enhance ecosystem resilience (Matocha, 2012). Understanding how these strategies can be implemented at a regional level is essential for improving mango cultivation sustainability, particularly in areas most affected by climate variability (Ogunbode, 2024).

1.1 Problem Statement

The impact of climate change on mango production is a growing concern for mango farmers, particularly in tropical and subtropical regions. Increasing temperatures, erratic rainfall, and the prevalence of extreme weather events are affecting mango flowering, fruit development, and yield. These changes threaten food security and the livelihoods of millions of people dependent on mango farming, necessitating the exploration of effective climate adaptation strategies.

1.2 Research Questions

1. How does temperature variability affect the phenology and yield of mango cultivars in tropical and subtropical regions?
2. What are the impacts of climate change on mango fruit quality, and how can these impacts be mitigated?

3. What adaptation strategies, such as genetic improvement and water management, are most effective in sustaining mango production under changing climatic conditions?

1.3 Research Objectives

1. To investigate the impact of temperature fluctuations and rainfall patterns on the flowering, fruit set, and overall yield of mango cultivars.
2. To examine the effects of climate change on mango fruit quality, including changes in sugar-acid content, texture, and shelf life.
3. To assess the effectiveness of adaptation strategies, including breeding programs and water management techniques, in maintaining mango productivity and quality under climate-induced stress.

1.4 Literature Review

Table 1: Literature Review on Climate Change Impacts on Mango Production

S.No.	Title	Material	Research Gap	Reference
1	Phenology and Fruit Growth Dynamics of Mango (<i>Mangifera indica</i> L.) in Greenhouse and Open Air in Mediterranean Climate	Mango cultivars (Keitt, Osteen, Tommy Atkins)	Limited understanding of the impact of high temperatures on mango fruit growth in Mediterranean climates	D Scuderi, 2023 (SpringerLink)
2	From orchard to table: understanding climate change impacts on mango production in India: a review	Mango trees in India	Need for cultivar-specific responses and adaptation measures	Halder et al., 2024 (ResearchGate)
3	Patterns of shifting phenostages and	Mango trees in India	Lack of comprehensive	Rajdip Halder, 2023

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	flowering time in	data on	(ResearchGate)
	mango (<i>Mangifera</i>	phenological	
	<i>indica</i> L.) due to	shifts across	
	climate change	different mango	
		varieties	
4	Climate-Induced Heat Mango	Limited	AK Kushwaha,
	Stress Responses on cultivars	information on	2025 (MDPI)
	Indigenous Varieties (Amrapali,	heat stress	
	and Elite Hybrids of Mallika,	responses in	
	Mango (<i>Mangifera</i> Langra,	indigenous	
	<i>indica</i> L.) Dashehari,	mango cultivars	
	Himsagar,		
	Bombay		
	Green, Sharda		
	Bhog, Kesar,		
	Rataul)		
5	Climate change and Mango	Need for	Aragón et al.,
	agriculture: farmers in	strategies to	2019 (arXiv)
	Subsistence farmers' Peru	mitigate heat	
	response to extreme	stress effects on	
	heat	mango	
		cultivation	
6	Climate changes and Mango	Insufficient data	IGMIN
	mango production orchards in	on the effects of	Research, 2023
	(temperature) India	temperature	(IgMin
		variability on	Research)
		mango	
		productivity	
7	Climate-Induced Mango	Need for	Sharma et al.,
	Changes in Mango orchards in	integrated pest	2025
	Production: India	management	(SpringerLink)

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	Phenological Impacts, Pest Threats, and Mitigation Approaches		approaches under changing climate conditions	
8	Fruit orchards under climate change conditions: adaptation strategies and management	Fruit orchards in arid regions	Lack of specific adaptation strategies for mango orchards under climate stress	MedCrave Online, 2021 (MedCrave Online)
9	Integrating climate change adaptation and mitigation through agroforestry and ecosystem conservation	Mango orchards in India	Need for region-specific agroforestry models for mango cultivation	Matocha, 2012 (ResearchGate)
10	Understanding the Perception of Mango (Mangifera indica) Farmers on the Impact of Climate Change on Mango Farming in Nigeria	Mango farmers in Nigeria	Limited understanding of farmers' perceptions and adaptation strategies	Ogunbode, 2024 (Wiley Online Library)
11	Predicting the potential geographical distribution of mango, an important tropical economic tree species, under current and climate change based on Maxent model	Mango cultivation areas in China	Need for models incorporating mango variety-specific responses to climate change	Yi, 2025 (Frontiers)
12	Assessment of the Mango		Lack of studies	Singh et al.,

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- differential trade-off saplings on the 2023
between growth, (Amrapali, differential trade- ([ScienceDirect](#))
subsistence, and Mallika) offs in mango
productivity of two under climate-
popular Indian hybrid induced stress
mango varieties under
elevated ozone
exposure
- 13 Comparative Mango fruits Need for safer Obadiah et al.,
Evaluation of the in Nigeria and more 2024 ([arXiv](#))
Proximate and effective ripening
Cytogenotoxicity of agents for mango
Ash and Rice Chips fruits
Used as Mango Fruit
Artificial Ripening
Agents in Birnin
Kebbi, Nigeria
- 14 Climate change and Mango Need for Aragón et al.,
agriculture: farmers in strategies to 2019 ([arXiv](#))
Subsistence of farmers' Peru mitigate heat
response to extreme stress effects on
heatClimate-smart mango
agriculture: cultivation
perspectives and
framings
- 15 Phenology and Fruit Mango Need for region- Chandra, 2018
Growth Dynamics of farming specific climate-
Mango (*Mangifera* systems smart practices
indica L.) in globally for mango
Greenhouse and Open farming
Air in Mediterranean
-

Climate

The effects of climate change on mango production are evident and pose significant challenges to the agricultural sector in many countries. As mango cultivation is highly susceptible to changes in temperature, precipitation, and extreme weather events, it is crucial to understand the full extent of these impacts and identify strategies to mitigate them. By focusing on understanding how climate change affects mango phenology, yield, and quality, and exploring viable adaptation strategies, this research aims to provide valuable insights for improving mango cultivation sustainability in a changing climate.

2. Phenological Changes in *Mangifera indica* L. Due to Climate Change

Phenology, the study of the timing of biological events such as flowering, fruiting, and ripening, plays a crucial role in the success of mango cultivation. Climate change, characterized by rising temperatures and altered precipitation patterns, has been shown to disrupt the phenological cycles of mango trees, leading to shifts in the timing of these key events. In a typical mango growing season, flowering generally occurs between January and March (Singh et al., 2020). This period is followed by fruit set and early development from March to May. Climate change, particularly increased temperatures, has been linked to earlier flowering in some mango varieties, resulting in an earlier fruit set. However, excessive heat during flowering can lead to reduced pollination success and flower drop (Gupta et al., 2021). The fruiting stage typically spans from May to June, with fruit ripening occurring between June and August (Sharma et al., 2023). Altered temperature and humidity during this period can result in inconsistent fruit maturation, affecting both the yield and quality. Mangoes may ripen too quickly, leading to a reduction in shelf life and marketability. The changing climate also increases the vulnerability of mango trees to pest outbreaks, which can further affect fruit quality and yield (Kumari et al., 2022).

2.1 Temperature Impact on Mango Phenology

Temperature plays a significant role in the phenology of *Mangifera indica* L. (mango), influencing flowering, fruit set, and development. Elevated temperatures have been linked to earlier flowering in certain mango varieties, such as the *Mangifera indica* cv. Alphonso and Kesar (Singh et al., 2020). Warmer conditions can induce mango trees to flower earlier than typical seasonal patterns, potentially altering fruiting times

and yield. However, while slight temperature increases can promote early flowering, excessive heat during critical stages of flowering and fruit set can lead to detrimental effects, including flower drop, reduced fruit set, and poor fruit development (Gupta et al., 2021). High temperatures, especially during flowering, cause incomplete pollination, resulting in the abortion of fruits. The excessive heat stresses the reproductive tissues, leading to the failure of pollen grains to fertilize flowers effectively (Kumari et al., 2022). Conversely, prolonged cool periods, typically associated with lower-than-normal temperatures during the flowering phase, can delay the timing of flowering and fruit ripening, as observed in varieties like Haden and Tommy Atkins (Sharma et al., 2023). These delays can have cascading effects on the overall growth and development of mango fruit, leading to a reduction in the uniformity of ripening and potentially compromising fruit quality. Additionally, cool weather can impair the enzymes necessary for proper maturation, resulting in poor flavor development and decreased marketability (Singh et al., 2020). In summary, while temperature influences the timing and quality of mango flowering and fruiting, the balance between heat and cool conditions is critical for optimal mango cultivation. Understanding the specific temperature requirements of different mango varieties is essential for maintaining consistent production and fruit quality under changing climatic conditions.

2.2 Rainfall and Humidity Impact on Mango Phenology

Erratic rainfall patterns and increased humidity levels, both consequences of climate change, have profound effects on the phenology and quality of *Mangifera indica* L. (mango). Excessive rainfall during the flowering and fruiting stages can create favorable conditions for the proliferation of fungal diseases, such as anthracnose (*Colletotrichum gloeosporioides*), which are detrimental to mango quality. Anthracnose causes lesions on fruit, reducing marketability and leading to significant post-harvest losses (Singh et al., 2020). In regions with high rainfall, these diseases can spread rapidly, diminishing fruit yield and affecting the overall agronomic performance of mango orchards. In addition to disease pressure, increased humidity can influence the mango ripening process. High humidity levels extend the duration of fruit ripening, leading to inconsistent maturation. This inconsistency can result in mangoes that are overripe or underdeveloped at the time of harvest, affecting flavor,

texture, and shelf life. Furthermore, prolonged ripening periods may cause the mango skin to become more prone to fungal infections and rot, further compromising the quality (Gupta et al., 2021). The combination of erratic rainfall and increased humidity challenges mango farmers by reducing fruit uniformity and increasing the risk of crop failure. Adapting management practices, such as using fungicide treatments, improving drainage, and selecting resistant varieties, can help mitigate these climate-induced challenges (Kumari et al., 2022).

3. Agronomic Performance of *Mangifera indica* L. Under Climate Change

Agronomic performance refers to the overall growth characteristics and productivity of mango trees. Climate-induced stresses, such as drought, temperature fluctuations, and changes in soil moisture, significantly impact mango trees, reducing their ability to thrive and produce optimal yields.

3.1 Water Stress and Irrigation

Water availability is one of the most crucial factors influencing mango production. In many mango-growing regions, particularly in arid and semi-arid climates, climate change is expected to exacerbate water scarcity (Sharma et al., 2023). Reduced water availability leads to stunted tree growth, decreased fruit size, and lower overall yield (Gupta et al., 2021). Prolonged drought conditions can also increase the vulnerability of mango trees to pests and diseases, as stressed trees are less resilient to pathogen attacks. To mitigate these effects, adaptation strategies such as efficient irrigation systems (e.g., drip irrigation), rainwater harvesting, and the use of drought-resistant mango varieties are vital. These strategies can help ensure a steady water supply during dry periods, improving tree health and maintaining productivity (Kumari et al., 2022).

3.2 Soil Health and Fertility

Climate change impacts soil health and fertility by altering rainfall patterns and temperature, which in turn affects soil moisture and nutrient availability (Singh et al., 2020). Reduced rainfall can lead to lower soil moisture levels, while increased temperatures can cause rapid evaporation, further reducing available water for mango trees. Soil degradation, including erosion and loss of organic matter, is also exacerbated by erratic rainfall patterns, particularly in regions with heavy rains (Gupta et al., 2021). These factors result in poor tree growth, nutrient deficiencies,

and reduced fruit yield. Addressing these challenges requires sustainable land management practices, such as mulching, agroforestry, and soil conservation techniques, to maintain soil fertility and prevent erosion.

4. Yield and Productivity of *Mangifera indica* L. Under Climate Change

The yield and productivity of *Mangifera indica* L. (mango) are directly influenced by climate variables such as temperature, precipitation, and atmospheric CO₂ concentrations. Climate change is expected to exacerbate challenges to mango production, reducing yields and compromising the quality of fruit in affected regions.

4.1 Temperature and Yield

Rising temperatures have a profound impact on mango yield, particularly during critical stages such as flowering and fruit set. High temperatures, especially during flowering, can impair the pollination process by affecting pollen viability and reducing fertilization rates, ultimately leading to lower fruit set (Gupta et al., 2021). Furthermore, elevated temperatures accelerate fruit ripening, which shortens the shelf life of mangoes and negatively impacts their marketability (Singh et al., 2020). Studies have shown that when temperatures exceed the optimal range for mango growth—typically between 24°C and 30°C—yield declines significantly due to poor fruit development and reduced fruit retention (Sharma et al., 2023). Mango varieties such as Alphonso and Haden, which are highly sensitive to temperature fluctuations, experience reduced productivity when exposed to higher-than-usual temperatures during the flowering and fruit maturation stages.

4.2 Extreme Weather Events

In addition to temperature increases, extreme weather events such as storms, floods, and heatwaves are becoming more frequent due to climate change. These events can cause severe damage to mango orchards, leading to significant loss of both fruit and trees. Cyclones and heavy rains can uproot trees, break branches, and cause fruit drop, directly reducing yield (Kumari et al., 2022). Moreover, intense heat events can result in heat stress, which inhibits photosynthesis and slows down the growth and development of mango trees (Gupta et al., 2021). Such stressors weaken the trees, making them more susceptible to pests and diseases, further reducing productivity and fruit quality. The increasing frequency of these extreme events highlights the vulnerability of mango production and the need for adaptive strategies, such as the

development of resilient mango varieties and improved orchard management practices, to maintain productivity.



Figure 1: Pakistani Farmers Pin Poor Mango Crop on Climate Change

5. Fruit Quality of *Mangifera indica* L. Under Climate Change

The quality of mangoes, which is defined by characteristics such as sweetness, acidity, texture, and shelf life, is highly influenced by climate factors. As climate change continues to alter environmental conditions, these quality attributes are increasingly at risk due to changes in temperature, humidity, and rainfall patterns.

5.2 Sugar and Acid Content

Higher temperatures have been shown to increase the sugar content in mangoes, enhancing their sweetness (Singh et al., 2020). However, excessive heat can disrupt the balance between sugar and acid, leading to a less favorable taste. High temperatures accelerate the maturation process, causing a higher rate of sugar accumulation while diminishing the acidity, which is crucial for maintaining a balanced flavor profile (Gupta et al., 2021). This imbalance results in mangoes that may taste overly sweet or lack the characteristic tanginess that consumers expect. In addition, irregular rainfall patterns during the growing season can delay or speed up fruit ripening, contributing to inconsistent texture and flavor. Mangoes that ripen unevenly often exhibit variations in texture, making them less desirable for consumption and affecting their market value.

5.3 Post-Harvest Quality

Climate change also affects the post-harvest quality of mangoes, especially in terms of shelf life. Increased temperatures and humidity levels during storage accelerate the ripening process, which can lead to quicker spoilage (Kumari et al., 2022). This is a significant concern for mangoes intended for export, where long-distance

transport is required. The faster ripening rate in higher humidity and temperature conditions may cause the fruit to over-ripen before reaching its destination, leading to a loss in marketable quality and an increase in post-harvest losses. Effective post-harvest management, such as controlled atmosphere storage and temperature regulation, is necessary to mitigate these effects and extend the shelf life of mangoes.

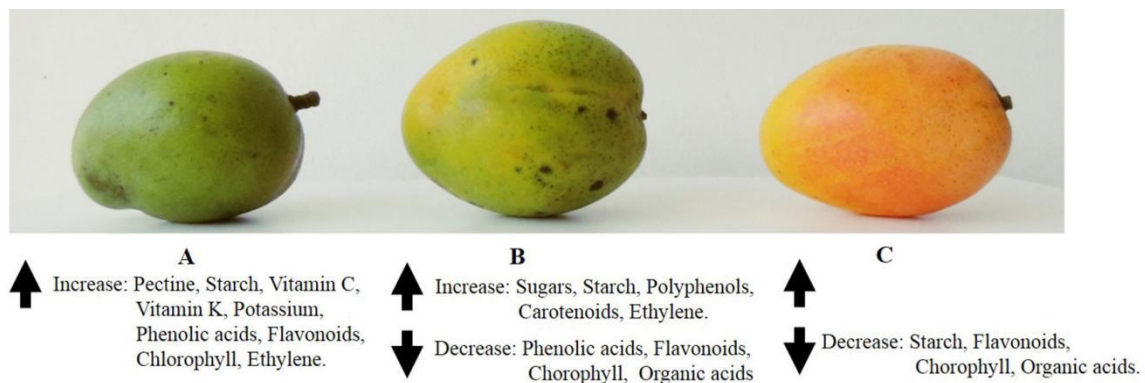


Figure 2: Post-Harvest Quality of Mangoes, Especially in Terms of Climate Change

6. Adaptation Strategies for Mitigating Climate Change Impacts on Mango Production

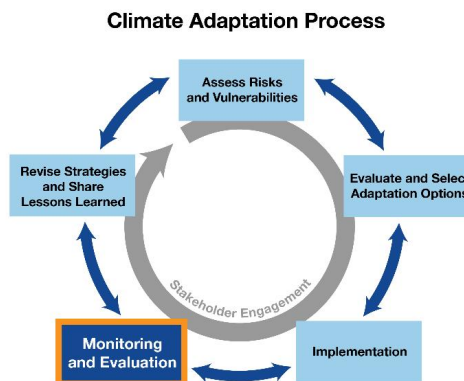


Figure 3: Adaptation Monitoring and Evaluation of Climate Change Impacts

As climate change continues to alter environmental conditions, mango growers must adopt adaptive strategies to ensure sustainable production. Several effective approaches have been identified to mitigate the adverse impacts of climate change on mango cultivation, focusing on genetic improvement, water management, pest control, and agricultural diversification.

6.1 Genetic Improvement

One of the most promising strategies for adapting mango cultivation to climate change is the development of climate-resilient mango varieties. Breeding programs can focus on selecting varieties that are more tolerant to heat, drought, and disease. Varieties like *Mangifera indica* cv. Alphonso and Haden, which are sensitive to extreme weather conditions, can be replaced or genetically enhanced to improve their resilience to temperature fluctuations and water stress (Kumari et al., 2022). Moreover, breeding for improved fruit quality under varying climatic conditions can help maintain both yield and marketability.

6.2 Water Management

Efficient water management is essential to mitigate the impacts of drought and erratic rainfall on mango trees. Drip irrigation systems are an effective way to optimize water use by providing targeted moisture directly to the roots, minimizing water wastage (Gupta et al., 2021). Rainwater harvesting techniques can also supplement irrigation systems during dry periods, providing an additional water source that helps maintain consistent growth and fruit development (Singh et al., 2020).

6.3 Integrated Pest Management (IPM)

Climate change can alter pest and disease dynamics, as warmer temperatures and humidity favor the proliferation of pests such as *Dysmicoccus brevipes* (mango mealybug) and fungal pathogens like anthracnose (*Colletotrichum gloeosporioides*). Integrated pest management (IPM) systems combine biological, cultural, and chemical control methods to reduce pest populations while minimizing environmental harm. IPM strategies help ensure higher fruit quality and yield by reducing pest-related damage (Sharma et al., 2023).

6.4 Agroforestry

Agroforestry involves planting mango trees alongside other crops or incorporating trees into a diverse farming system. This practice can buffer against extreme weather events such as storms, droughts, and floods. The integration of mango trees with other crops enhances biodiversity, improves soil health, and provides an additional source of income for farmers (Kumari et al., 2022). Moreover, agroforestry

can help manage temperature extremes by providing natural shade for mango trees, thus reducing heat stress during peak summer months.

6.5 Diversification of Farming Systems

Diversifying farming systems can reduce the risk of total crop failure due to climate variability. Growing multiple crops alongside mangoes ensures that if one crop fails due to climate-induced stress, others may still thrive. Diversification also allows farmers to better manage market risks and stabilize their incomes (Gupta et al., 2021). For example, growing drought-resistant crops alongside mango trees can help balance water usage and reduce the impact of reduced rainfall on mango production.

6.6 Improved Soil Management

Soil health is integral to the agronomic performance of mango trees. Practices such as mulching, crop rotation, and reduced tillage can improve soil fertility and moisture retention. The use of organic fertilizers and composts can help maintain soil structure and nutrient content, particularly in areas affected by erratic rainfall and temperature fluctuations (Singh et al., 2020).

6.7 Climate-Resilient Orchard Management

Orchard management practices, including proper tree spacing, pruning, and pest management, can improve mango tree resilience to climate stressors. Adjusting planting schedules to align with shifting climatic patterns is also important. For example, planting mango trees during the early rainy season may mitigate the effects of future droughts (Sharma et al., 2023).

6.8 Temperature-Controlled Storage

Increased temperatures during mango ripening and post-harvest storage can reduce shelf life and fruit quality. Implementing controlled atmosphere storage systems can help slow down the ripening process, ensuring that mangoes maintain their quality during transport and storage, especially for export markets (Kumari et al., 2022).

6.9 Use of Climate-Smart Practices

Farmers can adopt climate-smart practices such as adjusting planting dates, selecting suitable mango varieties for changing conditions, and adopting water-efficient irrigation systems. These practices help to increase the resilience of mango production systems to the impacts of climate change while enhancing productivity

(Gupta et al., 2021).

6.10 Policy Support and Capacity Building

Governments and agricultural institutions must provide policy support, technical guidance, and financial resources to help farmers implement adaptation strategies. Capacity building programs, such as training on water management, pest control, and agroforestry, will equip farmers with the tools needed to cope with the impacts of climate change on mango production (Singh et al., 2020). Adaptation strategies such as genetic improvement, efficient water management, integrated pest management, agroforestry, and diversification of farming systems are essential for mitigating the impacts of climate change on mango production. By adopting these strategies, mango growers can enhance resilience, maintain productivity, and ensure sustainable mango cultivation in a changing climate.

8. Conclusion

The impacts of climate change on mango production are profound and multifaceted, influencing various aspects of mango cultivation, including phenology, yield, and fruit quality. As temperatures rise and rainfall patterns become more erratic, the timing of flowering, fruit set, and ripening are disrupted, leading to reduced fruit quality and inconsistent yields. In addition to temperature fluctuations, increased humidity and rainfall contribute to the proliferation of pests and diseases, further challenging mango production systems. Furthermore, water scarcity exacerbated by climate change impacts tree growth, fruit size, and yield, making effective water management a crucial component of climate adaptation. To ensure the sustainability of mango production in a changing climate, several adaptation strategies must be implemented. These strategies include developing climate-resilient mango varieties through breeding programs, adopting efficient water management techniques such as drip irrigation and rainwater harvesting, and implementing integrated pest management (IPM) systems. Agroforestry practices and crop diversification also offer valuable solutions to buffer against extreme weather events and enhance the resilience of mango orchards. Despite the wealth of research on climate change impacts, there remain significant gaps in understanding the cultivar-specific responses to climate variability and the need for region-specific adaptation strategies. Further studies are required to explore these areas and develop practical, scalable

solutions. In conclusion, addressing the challenges posed by climate change is essential for safeguarding mango production, and a combination of genetic, environmental, and management approaches will be vital for ensuring the future viability of this important crop.

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