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GUAVA CULTIVATION UNDER CHANGING CLIMATE: NUTRITIONAL AND STRESS ADAPTATION APPROACHES

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Abstract

Guava (Psidium guajava L.), valued for its high nutritional profile and adaptability, faces significant challenges from climate change-induced abiotic stresses including terminal heat, drought, and soil salinity, which disrupt phenology, reduce fruit set, impair photosynthetic efficiency, and lower overall productivity. This review synthesizes physiological (antioxidant enzyme upregulation, Osmo protectant accumulation), biochemical (ROS scavenging, ion homeostasis), and molecular (differentially expressed ESTs, miRNAs targeting auxin and stress signaling) adaptation mechanisms in tolerant cultivars such as 'Surahi (R)'. Nutritional interventions (foliar zinc, boron, silicon, calcium, salicylic acid) and biostimulants enhance stress resilience, while high-density planting, meadow orcharding, precision canopy management, and resilient rootstocks ('Crioula') improve resource-use efficiency and yield stability. Integration of transcriptomics, value addition, and postharvest technologies further supports climate-smart guava cultivation. These approaches collectively offer practical strategies to sustain production, maintain fruit quality, and ensure nutritional security in vulnerable tropical and subtropical regions under projected climate scenarios.

1. Introduction

The global horticultural sector faces an unprecedented challenge as anthropogenic climate change disrupts traditional cultivation cycles, particularly for tropical and subtropical perennials. Guava (Yeshiwas et al., 2026). Often heralded as the "Apple of the Tropics," occupies a vital niche in the agricultural economies of over 60 countries due to its exceptional nutritional profile, high Vitamin C content, and relative hardiness (Tucker & Buranapin, 2001). however, the sustainability of guava production is currently besieged by a triad of environmental stressors: rising global temperatures, erratic precipitation patterns leading to prolonged droughts, and the progressive salinization of irrigation water and soil (Usman, 2023). These stressors do not act in isolation; rather, they form a complex web of physiological and biochemical challenges that reduce fruit set, compromise organoleptic quality, and diminish overall orchard productivity (Agrawal et al., 2025). To safeguard the future of this crop, a comprehensive understanding of its stress adaptation mechanisms ranging from transcriptional regulation to nutritional homeostasis is required (Saleem et al., 2025).

2. The Impact of Climate Variability on Guava Phenology and Yield

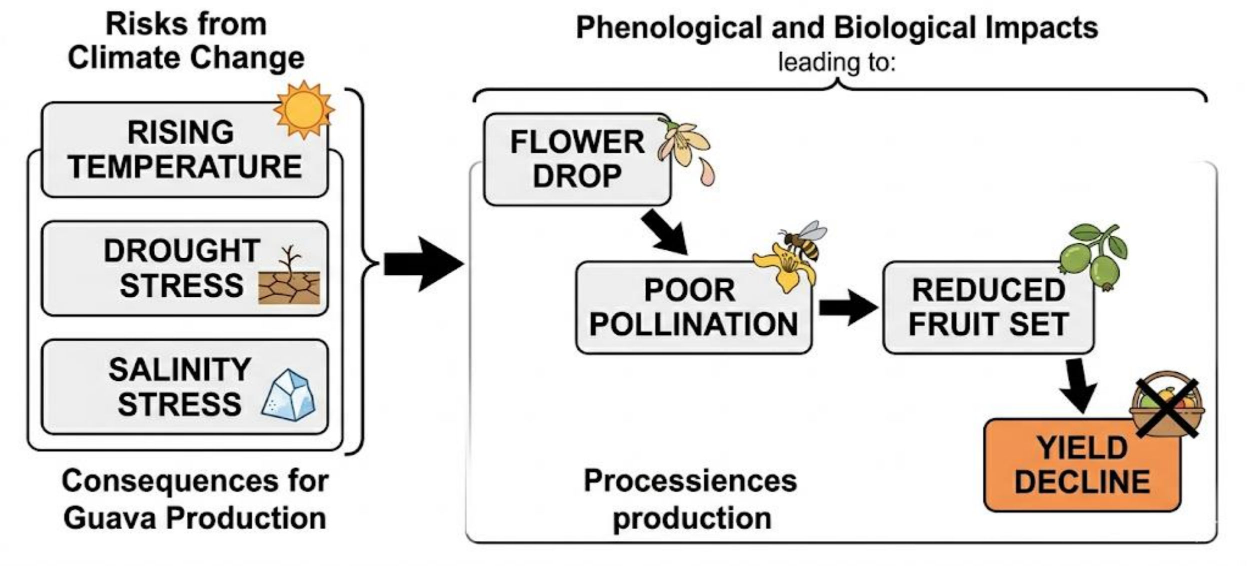
The transition from stable climatic regimes to volatile weather patterns has direct implications for the phenological synchronization of guava. As a crop that bears on current season emerging shoots, guava is sensitive to the timing and intensity of weather events that influence vegetative flushes and subsequent floral induction (Sarkar et al., 2021). Temperature fluctuations and unpredictable rainfall are now identified as primary drivers of irregular flowering and fruit set failures in South Asia and South America (Yadav et al., 2023).

2.1 Thermal Stress and Floral Abscission

Guava demonstrates a specific range of cardinal temperatures that dictate its growth potential. While the species can tolerate absolute maxima as high as 51.2°C, the optimal temperature for development is a more modest 17.3°C, with growth effectively ceasing when night temperatures fall between 5°C and 7°C (Sau et al., 2023). In recent years, regions such as the Pirojpur district in Bangladesh have reported that excessive heat during the flowering phase has led to the premature abscission of approximately one-third of blossoms (Karmakar, 2019). High atmospheric temperatures, particularly when coupled with low relative humidity, induce physiological disorders that inhibit pollen viability and fruit growth, although recent field data indicates that asynchronous maturity in certain genotypes may help avoid peak heat stress during the fruit-set phase (Mehmood et al., 2025).

Furthermore, the impact of thermal stress extends to the ecological services required for guava production. There is a documented positive correlation between honey bee density and guava fruit set, with active pollination boosting yields by 20% to 40% (Halder et al., 2019). However, rising temperatures and altered flowering patterns diminish pollinator activity and habitat stability, leading to a secondary yield decline through reduced fertilization success (Shivanna et al., 2020). To better visualize the cascading effects of climate variability on guava development, Figure 1 illustrates the direct pathways through which abiotic stresses disrupt phenological stages and ultimately reduce yield performance.

Figure 1. Climate Change Impacts on Guava Phenology and Yield



2.2 Drought Dynamics and Hydrological Imbalance

Water availability is perhaps the most significant determinant of guava productivity, with annual requirements varying between 1,000 mm and 2,000 mm depending on the agro-climatic zone. Drought stress induces a cascade of morphological and physiological retractions, including reduced shoot elongation, decreased leaf area, and lower fruit fresh weight (GOPAL, 2020). In Pakistan, where guava is the fourth most important fruit crop, production has declined significantly over the past five years due to its susceptibility to water dearth and abiotic extremes (Rangare et al., 2025). The plant's response to drought is characterized by a strategic reallocation of metabolic resources. Under a 50% field capacity regime, guava cultivars often exhibit a reduction in transpiration and CO_2 assimilation rates as a means of moisture conservation (Devin et al., 2013). However, this defense mechanism results in an overall decrease in biomass and fruit quality, as the competition for carbohydrates between vegetative and reproductive organs intensifies under stress (Pawar & Rana, 2019).

Table 1. Optimal environmental conditions and the impact of abiotic stress on guava phenology and yield.

Parameter	Optimal Conditions	Stress Impact (Drought/Heat)	Source
Temperature Range	20–30°C	Blossom drop at $T > 35°C$; growth halt at $T < 7°C$	(Fischer & Melgarejo, 2021; Usman et al., 2022)
Annual Rainfall	1,000–2,000 mm	Flowering and fruit set failure under deficit	(Fischer & Melgarejo, 2021)
Pollination Boost	20–40%	Reduced honey bee activity under habitat stress	(Rangare et al., 2025)
Water Use Efficiency	High in tolerant CVs	41.86% increase in 'Surahi' under 50% FC	(Usman et al., 2022)

3. Physiological and Biochemical Adaptation Mechanisms

To mitigate the deleterious effects of abiotic stress, guava plants employ a suite of adaptive strategies that operate at multiple biological scales. These include the upregulation of antioxidant scavenging systems, the accumulation of Osmo protectants, and the maintenance of leaf water potential through stomatal regulation (Manzoor et al., 2023).

3.1 Antioxidant Enzyme Scavenging Systems

Abiotic stress, whether induced by drought, salinity, or heat, invariably leads to the overproduction of reactive oxygen species (ROS), which cause oxidative damage to cellular membranes and proteins (Sachdev et al., 2021). Guava varieties with higher stress tolerance, such as the pear-shaped 'Surahi,' demonstrate a superior capacity for ROS detoxification (GOSWAMI, 2024). Under conditions of 50% field capacity, 'Surahi' exhibits an increase in Peroxidase (POD) activity by 402% and Catalase (CAT) activity by 170.21%. This enzymatic surge is complimented by the accumulation of non-enzymatic antioxidants, including flavonoids and proline, which reinforce the cell's structural integrity and facilitate osmotic adjustment (Saed-Moucheshi, 2021).

3.2 Osmoregulation and Secondary Metabolites

The accumulation of proline and soluble sugars serves as a critical buffer against the reduction of soil osmotic potential in both saline and water-scarce environments (Ikan et al., 2025). In the Brazilian semi-arid region, salinity levels above 1.8 dSm^{-1} trigger a metabolic shift where stress during the fruiting stage elevates the concentration of non-reducing sugars and improves the maturation index of the fruit. This indicates that while stress reduces overall yield, it may, under specific management, enhance certain chemical attributes of the fruit as the plant concentrates its remaining metabolites (Hussain et al., 2025). Furthermore, the synthesis of secondary metabolites like terpenes, alkaloids, and phenolics is positively correlated with plant resilience (Khan, 2025).

4. Transcriptional and Molecular Landscapes of Stress Tolerance

Recent advances in transcriptomics have begun to unravel the complex genetic networks that govern guava's resilience to climate change. The identification of Expressed Sequence Tags (ESTs) and microRNAs (miRNAs) provides a window into the molecular reprogramming that occurs when the plant is exposed to suboptimal conditions (Zaffar et al., 2025).

4.1 Comparative Transcriptomics of 'Surahi' and 'Gola'

A pivotal study comparing the drought-tolerant 'Surahi' with the more sensitive 'Gola' cultivar revealed a significant disparity in their transcriptional responses (Sonowal et al., 2025). 'Surahi' expressed nearly double the number of stress-responsive ESTs (234) compared to 'Gola' (117). These ESTs are primarily localized in the nucleus, cytosol, and plastids, suggesting a centralized regulation of the cellular network through signaling cascades (Lopez Tubau, 2024).

Key genes upregulated in the tolerant cultivar include:

- **Sucrose Synthase (SUS)**: Facilitates the regulation of sugar metabolism to maintain turgor pressure (Kaur et al., 2021).
- **Alcohol Dehydrogenase (ADH)**: Implicated in metabolic adaptation and fruit ripening under stress (Brizzolara et al., 2020).
- **Ubiquitin Family Genes**: Mediate proteolytic responses to environmental stimuli (Wettstadt & Llamas, 2020).
- **Transcription Factors**: Including RWP-RK family factors (like NLP7), which act as pivotal regulators of stress tolerance (Sámano et al., 2024).

Conversely, both cultivars share a core set of upregulated ESTs, such as PSI type III chlorophyll a/b-binding proteins and UDP-glycosyltransferase superfamily members, indicating a conserved baseline response to moisture deficit (Sahay et al., 2023).

4.2 MicroRNA Regulation under Salinity Stress

MicroRNAs (miRNAs) serve as post-transcriptional gatekeepers of stress signaling. In guava under salinity stress, several key miRNAs are differentially expressed, targeting transcripts involved in root architecture, flowering timing, and hormone signaling (Sahay et al., 2023).

Table 2. Key microRNA (miRNA) expression patterns and functional impacts under salinity stress in guava.

miRNA	Expression Pattern	Target/Pathway	Functional Impact
miR160/167	Downregulated	Auxin Response Factors (ARFs)	Inhibits lateral root formation under high salt
miR390	Downregulated	TAS3; AtBAM3 Kinase	Affects shoot and floral meristem formation
miR156	Downregulated	SPL mRNAs	Controls trichome patterning and flowering onset
miR162	Downregulated	DCL1 gene	Regulates the overall miRNA biogenesis pathway
miR393	Stress Responder	Auxin Receptors (TIR1/AFB2)	Represses growth to conserve energy during stress

5. Nutritional Strategies for Stress Amelioration

Maintaining nutritional homeostasis is essential for guava to withstand the physiological disruption caused by toxic ion accumulation and water deficit. Salt stress, in particular, causes a nutritional imbalance where Na^+ and Cl^- ions compete with essential macronutrients like N, K, and Ca for uptake sites (Abrar et al., 2022).

5.1 Macronutrient Dynamics and Ionic Homeostasis

Under optimal conditions, 'Paluma' guava requires leaf concentrations of 20–23 g kg-1 for Nitrogen and 14–17 g kg-1 for Potassium to achieve maximum productivity (Pandey, 2019). Salinity often reduces these levels, alongside Calcium and Magnesium, leading to cellular toxicity and fruit drop (Gulbagca et al., 2020). Research suggests that biostimulants like seaweed extracts and humic substances can help the plant reach a new state of nutritional homeostasis, potentially mitigating the yield drop caused by irrigation with saline water (EC_w \approx. 3.0 dSm^{-1}) (Aftab et al., 2026).

5.2 Micronutrient Interventions: Zinc and Boron

In rainfed and nutrient-deficient soils, the foliar application of Zinc and Boron has proven highly effective in improving both growth and fruit quality (Kashyap et al., 2022). A combined spray of 0.75% Zinc sulphate and 0.50% Boric acid has been documented to maximize plant height, canopy volume, and leaf chlorophyll content (Ibraheem & Mahmoud, 2024). Zinc is an essential constituent of several enzyme systems and is critical for auxin synthesis and protein production, while Boron plays a vital role in cell wall development, membrane integrity, and the translocation of carbohydrates to reproductive organs (Rudani et al., 2018).

5.3 The Role of Silicon and Calcium in Abiotic Resilience

Silicon (Si), often overlooked in traditional fertilization practices, provides important structural and physiological benefits to plants under stress conditions. When applied as Potassium Silicate (K2SiO3), silicon enhances drought tolerance by maintaining plant water balance and protecting xylem vessels from collapsing under high transpiration rates (Elakiya

et al., 2025). It also reduces the incidence of micronutrient and metal toxicity and has been shown to increase the total soluble solids (TSS) content in guava fruit (Khatun et al., 2024).
Similarly, external Calcium (Ca2+) ions play a dual role in strengthening plant cell walls and acting as a secondary messenger in drought-stress signaling (Wei et al., 2025). The external application of Ca2+ can restore Photosystem II activity and reduce the suppression of genes involved in the Calvin–Benson cycle and electron transport. As a result, it helps protect the photosynthetic system from irreversible damage under drought stress (Ayyaz et al., 2024).

Table 3. Recommended foliar nutrient concentrations and primary benefits for guava resilience under abiotic stress.

Nutrient	Recommended Foliar Concentration	Primary Benefit under Stress	Source
Salicylic Acid	1.2–1.6 mM	Enhances NPK uptake; protects chlorophyll pigments	(Parihar et al., 2025)
Zinc Sulphate	0.75%	Boosts auxin synthesis; increases fruit size	(Sharma et al., 2025)
Boric Acid	0.50–0.8%	Improves carbohydrate translocation; reduces fruit drop	(Rangare et al., 2025; Sharma et al., 2025)
Silicon (Si)	4 ml/L K_2SiO_3	Maintains water balance; increases TSS and yield	(Rangare et al., 2025)
Ascorbic Acid	600 mg L-1	Acts as biostimulant to increase fruit weight	(Ferreira et al., 2025)

6. Exogenous Bio-regulators and Biostimulants

The use of contemporary plant growth regulators (PGRs) and biostimulants offers an economically viable and practical method for enhancing climate resilience in guava (Kumar et al., 2022).

6.1 Salicylic Acid (SA) as a Stress Signaling Molecule

Salicylic Acid is a pivotal phenolic compound that activates defense genes and coordinates numerous physiological processes under stress (Chowdhary et al., 2022). Exogenous SA application (at 600 ppm or 1.2–1.6 mM) has been shown to:

- Increase the relative leaf water content and proline accumulation (Masheva et al., 2022).
- Protect photosynthetic pigments from degradation under salt and heat stress (Das et al., 2024).
- Reduce electrolyte leakage and cellular lipid peroxidation by enhancing antioxidant activity (Guo et al., 2018).
- Improve fruit set and weight under suboptimal moisture regimes (Talpur et al., 2023).

6.2 Brassinosteroids and Plant Extracts

Brassinosteroids (applied at 1 ppm) have demonstrated superior efficacy in maintaining chlorophyll levels compared to traditional PGRs under environmental fluctuations. Additionally, plant-derived extracts from guava leaves, aloe, (Ahanger et al., 2018) garlic, and alfalfa have been explored as "hormetic" agents that can effectively increase heat tolerance by improving water status and enhancing antioxidant defenses. These extracts minimize oxidative damage by decreasing levels of H_2O_2 and malondialdehyde (Verma et al., 2021).

7. High-Density Planting and Canopy Management Systems

Traditional guava orchards, characterized by wide spacing (6–7 m), often suffer from low productivity per unit area and large, unmanageable tree canopies that are vulnerable to climatic extremes (Tripathi, 2018). Modern horticultural practices are shifting toward High-Density Planting (HDP) and Meadow Orcharding to maximize resource-use efficiency (Dustmohamadi & Houshmand, 2025).

7.1 Meadow Orchard and Ultra-High Density (UHD)

Meadow orcharding is a novel concept that accommodates up to 5,000 trees per hectare at a spacing of 1.0 x 2.0 m. This system relies on intensive canopy management, including regular topping and hedging, to maintain a small, productive framework (Mia, 2021).

- **Yield Advantage:** Traditional systems yield approximately 12–20 t/ha, whereas HDP systems can achieve 30–50 t/ha (Muhie et al., 2026).
- **Early Bearing:** HDP trees reach full bearing faster (within 1–2 years) compared to traditional orchards (5–8 years) (Noble, 2021).
- **Resource Efficiency:** UHD systems are highly compatible with drip irrigation and fertigation, allowing for precise control over water delivery (Sood et al., 2025).

7.2 Pruning and Crop Regulation

Guava responds exceptionally well to canopy regulation, which is necessary to prevent excessive shading and maintain a balanced Carbon: Nitrogen (C: N) ratio for flowering. Regular pruning after fruit harvest encourages the development of new lateral shoots, which are the primary sites for flowering and fruiting (Jifon, 2023). Furthermore, rejuvenation pruning of old orchards can induce vigorous new growth and extend the commercial life of the trees (Munné-Bosch, 2018). In tropical climates, crop regulation strategies such as water stress induction or root exposure are employed to synchronize fruiting with the most profitable seasons (Sanaullah, 2024).

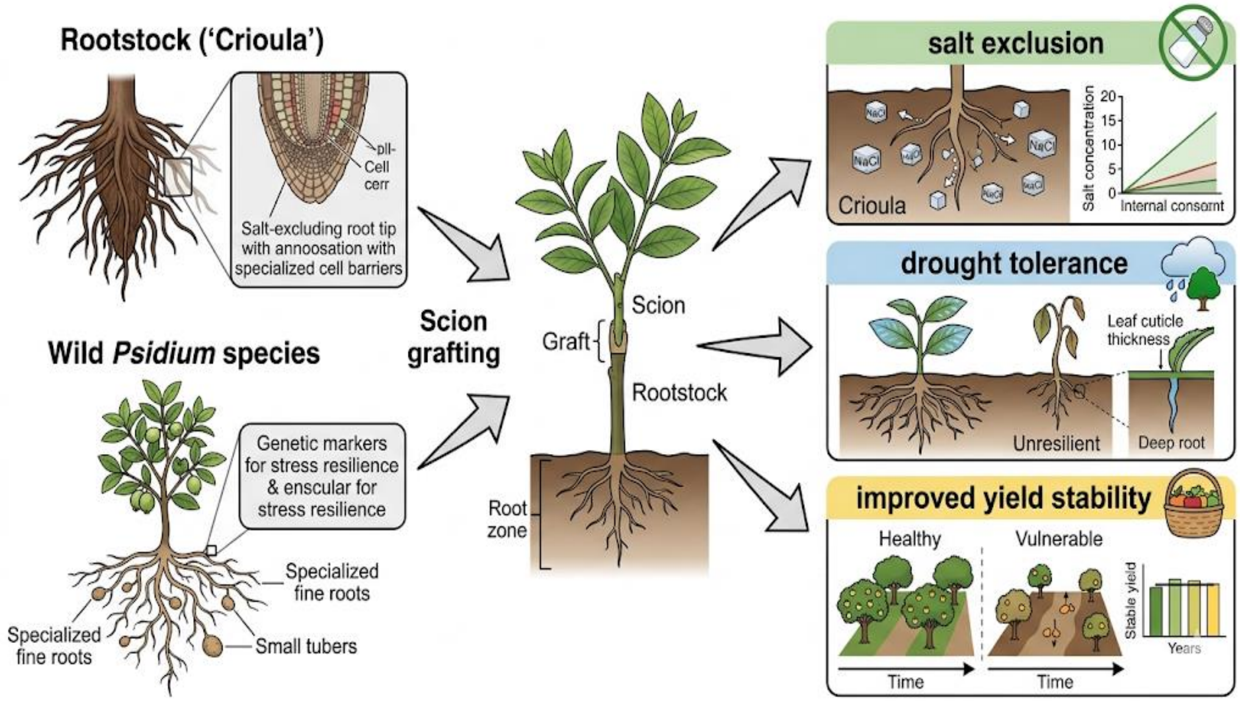
Table 4. Comparison of traditional, high-density (HDP), and meadow orchard planting systems in guava.

Feature	Traditional Orchard	High Density (HDP)	Meadow Orchard
Spacing	6 x 6 m	3 x 1.5 m	2 x 1 m
Trees per Hectare	Approx 277	2,222	5,000
Canopy Structure	Large, bushy	Managed central leader	Topped and hedged
Harvesting	Difficult	Easy/Manual	Easy/Mechanical potential
Light Penetration	Poor in the center	Good throughout	Excellent

8. Genetic Resources and Rootstock Resilience

The long-term solution to climate change in guava cultivation lies in the development of stress-tolerant varieties and the identification of resilient rootstocks (Dhurve et al., 2023). The contribution of rootstocks and wild genetic resources to stress tolerance and yield stability is illustrated in Figure 2.

FIGURE 2. Rootstock and Genetic Resource Contribution to Climate Resilience



8.1 Salt-Tolerant Rootstocks: 'Crioula' and Others

The identification of rootstocks capable of surviving high soil salinity is a priority for semi-arid agriculture (Mustapha et al., 2025). Studies have classified 'Crioula' guava as significantly more tolerant to salt stress as 'Paluma' or 'Ogawa,' with higher survival rates and better phytomass accumulation at salinity levels up to 1.8 dS m-1 (Singh et al., 2018). Selecting for rootstocks that can exclude toxic Na+ ions or sequester them in roots prevents the ions from reaching the sensitive scion leaves (Chakraborty et al., 2018).

8.2 Wild Psidium Species and Interspecific Hybrids

The genus *Psidium* contains a vast reservoir of genetic diversity. Wild species like *Psidium guineense* and *Psidium cattleianum* have been evaluated for their resistance to guava decline and other biotic stressors (Nagaraja et al., 2025). However, some wild species, such as *P. cattleianum,* may actually enhance Sodium uptake into the scion, suggesting that breeding programs must carefully evaluate graft combinations (Mauro et al., 2022). Resistance to nematodes is also being explored in *P. guineense*, where the synthesis of terpenes and phenolics provides a biochemical defense mechanism (Eloh et al., 2020).

9. Value Addition and Postharvest Resilience

Climate change not only affects the production of guava but also its postharvest longevity and economic value (Yeshiwas et al., 2026). Rising temperatures accelerate fruit ripening, leading to high annual losses in countries like Kenya, where processing remains low (3.1%) (Owino et al., 2025)

9.1 Processing and Waste Reduction

Despite being a "superfruit," guava is highly perishable. Developing a structured value chain that includes processing the pulp into jams, jellies, and juices is essential for stabilizing farmer incomes. Preservation technologies such as modified atmosphere packaging and the application of calcium chloride have been shown to extend shelf life (McDonell & Wilk, 2020).

9.2 The Role of Precision Horticulture and Automation

By 2030, global freshwater demand is predicted to outpace supply by 40%, making water-saving technologies essential (Water, 2024). Future guava production systems will likely incorporate:

- **Soilless Systems and CEA**: Controlled Environment Agriculture provides precise control over light, water, and nutrients (Neo et al., 2022).
- **Precision Irrigation**: Sensors and AI-driven models can continuously adapt irrigation schedules (Kaushik & Singh, 2025).
- **Biodegradable Media**: The shift toward coconut coir and hemp fiber supports circular economy principles (Vieira et al., 2024).

Conclusion:

Climate change poses multifaceted threats to guava cultivation through elevated temperatures, erratic rainfall, and increasing soil salinity, disrupting phenological synchronization, pollination services, photosynthetic capacity, and fruit quality while reducing yields in major producing regions. However, guava exhibits considerable adaptive plasticity through enhanced antioxidant systems, osmolyte accumulation, efficient ion compartmentalization, and transcriptional reprogramming involving key genes and miRNAs. Strategic nutritional management with zinc, boron, silicon, calcium, and biostimulants such as salicylic acid, combined with modern orchard systems including high-density planting, meadow orcharding, and precision canopy regulation, can significantly mitigate stress impacts and boost productivity per unit area. Leveraging tolerant rootstocks, wild germplasm, and emerging molecular tools will accelerate the development of climate-resilient varieties. To ensure long-term sustainability, future efforts should integrate precision irrigation, protected cultivation, value addition for waste reduction, and policy support for smallholders. By adopting these integrated physiological, agronomic, and biotechnological strategies, guava production can remain viable and economically rewarding, contributing to nutritional security and rural livelihoods in a warming world.

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