Optimization of Hot Water and Pulsed Electric Field Treatment for Extending Shelf Life of Guava (Psidium guajava L. cv. Allahabad Safeda) during Cold Storage

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Article

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Abstract:

This study investigated the combined effects of hot water treatment (HWT) and pulsed electric field (PEF) on the postharvest quality and shelf life extension of guava (*Psidium guajava L. cv. Allahabad Safeda*) during 28 days of cold storage at 5 ± 3°C. Fruits were subjected to HWT at varying temperatures (30–60°C for 3min) followed by PEF treatments (1–3 kV/cm, 10–100 µs pulse duration). Key physicochemical parameters including cumulative physiological loss in weight (CPLW), electrolyte leakage (EL), firmness, total soluble solids (TSS), and titratable acidity (TA) were monitored weekly. Results demonstrated that combined treatment at 45°C with moderate PEF intensity significantly reduced CPLW by 27% (from 15.6% to 8.66%), preserved firmness (retaining 67% of initial firmness versus 44% in control), and stabilized TSS and TA levels compared to untreated controls. Decay development was reduced by 65% at day 28. The treatment maintained better membrane integrity, as evidenced by 14% lower electrolyte leakage compared to controls. Additionally, correlation analysis was performed to assess relationships between treatment parameters and quality outcomes. Strong correlations (R^2 = 0.78-0.95) were observed between treatment conditions and key quality indicators, providing insights for optimizing postharvest handling protocols. This non-chemical preservation approach demonstrates significant potential for extending the commercial shelf life of guava, particularly for the Indian fruit export industry, where Allahabad Safeda is a major cultivar.

Keywords: Postharvest quality, Pulsed electric field, Heat treatment, Shelf life extension, Cold storage, Guava preservation, Non-thermal processing

1. Introduction

Guava (*Psidium guajava L.*) is a highly perishable tropical fruit that is prone to rapid postharvest quality deterioration [1]. Extending their shelf life is essential for facilitating broader distribution and improving marketability. Traditionally, low-temperature storage has been the principal method for preserving fruit quality; however, its effectiveness is often constrained by the continuation of enzymatic activity, even at reduced temperatures [2,3]. To overcome these limitations, several postharvest intervention strategies have been explored in the past. While HWT has shown efficacy in extending the shelf life and controlling pests in fruits such as mango [4–6] and banana [7]. Its effects remain inconsistent across species [8,9] Notably, HWT studies specific to guava are limited, focusing primarily on issues such as rot control and the enhancement of cold storage outcomes[10,11].

PEF technology is a non-thermal alternative that significantly enhances the safety and quality of fresh produce [12]. By delivering high-voltage electric pulses, PEF induces electroporation in cell membranes, leading to microbial inactivation while preserving essential nutrients, vitamins, and bioactive compounds that are otherwise compromised by thermal processes [13,14]. In addition to improving sensory characteristics, PEF facilitates nutrient extraction and improves processing efficiency[15]. Previous research has demonstrated that PEF improves textural properties, such as crispness and cohesiveness, in various fruits and vegetables, including potatoes [16,17] strawberries[18], apples [19],pineapples[20] and carrots [21]. However, the combined application of PEF and other mild treatments, such as HWT, remains underexplored, particularly for tropical fruits such as guava.

The optimization of postharvest treatment parameters requires systematic evaluation of multiple quality indicators over extended storage periods. Recent studies have demonstrated that statistical analysis of treatment-quality relationships can help identify optimal processing conditions [22–26]. Such approaches complement traditional experimental methods by revealing which parameters most strongly influence preservation outcomes [27]. Systematic correlation analysis enables identification of critical control points for maintaining fruit quality during storage.

Previous research has shown that the combination of PEF and mild heat can achieve significantly higher microbial inactivation than either method alone [28,29]. For example, treatments using PEF at 50 kV/cm in combination with sublethal temperatures have achieved up to a 7-log reduction in bacterial populations, including E. coli and L. innocua, while retaining key nutritional and sensory attributes [30,31]. This synergy provides a promising non-chemical alternative to conventional thermal pasteurization [32]. Therefore, the integration of HWT and PEF represents a sustainable strategy for extending guava shelf life and minimizing postharvest loss, in line with current global priorities in food preservation and safety. This study evaluates the combined HWT–PEF treatment for preserving quality of Allahabad Safeda guava during cold storage. While each technique has been studied individually in various fruits, systematic optimization of their combination specifically for guava cultivars remains limited. This research addresses this gap by identifying optimal treatment parameters that maximize shelf life while maintaining quality attributes. Additionally, we explore correlations between treatment conditions and quality outcomes, providing a foundation for developing practical preservation protocols suitable for adoption by the Indian fruit industry.

2. Materials and methods

2.1 Plant material and treatment

Allahabad Safeda guavas were procured from a local orchard in Chennai, Tamil Nadu. Fruits were selected based on uniform size, color, and absence of visible defects. Each fruit weighed approximately 0.25–0.30 kg. Prior to treatment, the fruits were sanitized by washing in 0.05 g/L chlorinated water at 25 °C for 1 min to eliminate surface microorganisms. Six treatment groups were formed. Five experimental groups were subjected to HWT at different temperatures—30 °C, 45 °C, 50 °C, 55 °C, and 60 °C—for 3 min, while one control group was treated with water at ambient temperature. Each treatment group consisted of 10 fruits, and the entire procedure was replicated thrice to ensure reproducibility and reduce the impact of random variation. Following HWT, the guavas were subjected to PEF treatment. The treatment chamber consisted of a parallelepiped methacrylate container fitted with two parallel stainless steel electrodes (dimensions: 20 × 5 cm), spaced 5 cm apart. The guavas were placed parallel to the electrodes and immersed in an aqueous solution with a conductivity of 10 µS/cm. The PEF treatment was applied using field strengths ranging from 1 to 3 kV/cm, with pulse durations between 10 and 100 µs and total cumulative treatment times ranging from 1 to 5 min [21]. The treatment parameters for both HWT and PEF were selected based on the effective ranges reported in previous studies involving similar perishable fruit types [33]. After treatment, the fruits were stored at 5 ± 3 °C and 80–90% relative humidity [11]. Sampling was conducted weekly to evaluate the key physicochemical quality parameters throughout the storage period. An illustration of the experimental setup is shown in Figure 1

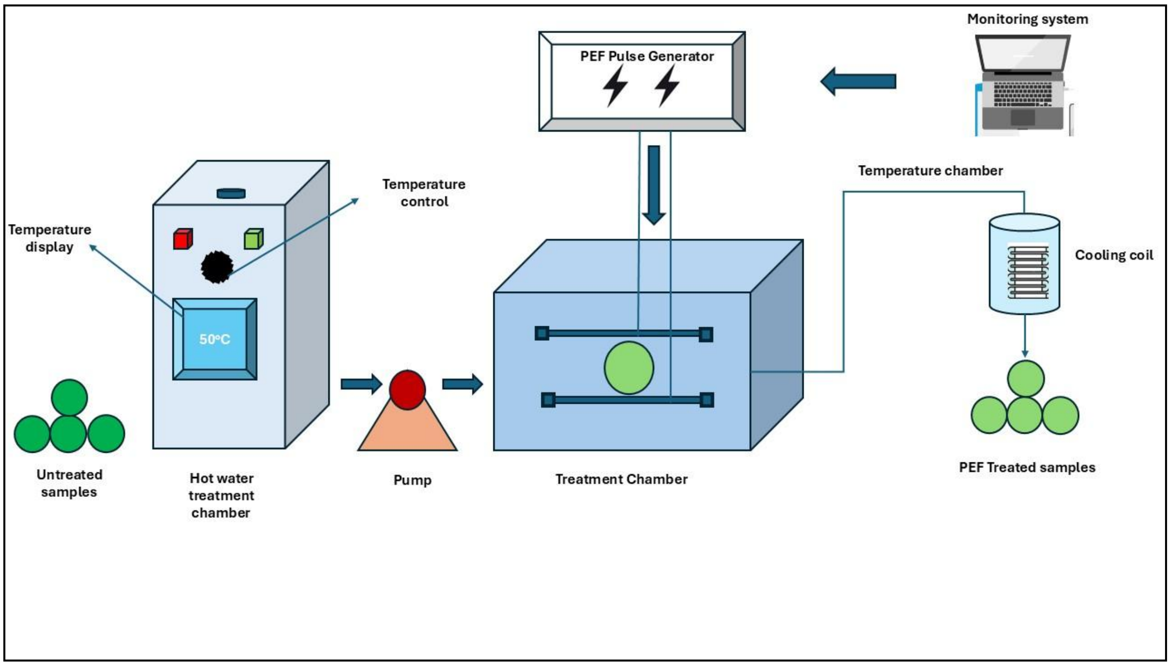

Figure 1 Illustration of experimental setup

2.2 Physicochemical and Biochemical Analysis

2.2.1 Weight and density

The weight of each fruit was measured using an RAF electronic compact scale model SF- 400 A. Fruit density was determined using the water displacement method, and all measurements were carefully recorded as per the method described by P. Pugazhendi et.al., [34].

2.2.2 Firmness

Fruit firmness was evaluated using a TA-XT 2 texture analyzer (Stable Micro Systems, UK). A stainless-steel compression plate with a diameter of 0.075 m was used to compress the fruit to a depth of 0.003 m at a constant speed of 0.001 m/s. Firmness values were recorded in Newtons (N).

2.2.3 CPLW

CPLW was calculated by monitoring the change in fruit weight over time and expressing it as a percentage relative to the initial weight using the following equation.

$$\text{CPLW} (\%) = \left[\frac{(W_1 - W_2)}{W_1}\right] \times 100 \qquad (1)$$

Where:

W1 - The initial weight of the fruit sample.

W2 -The weight of the fruit sample at a later point in time during sampling

2.2.4 EL

The measurement of EL from the fruit employed a method described by M. Schirra et.al., [35]. Six random peel tissue samples (10 mm diameter) were collected from each fruit using a cork borer. The samples were placed in 25 mL of 0.4 mol/L mannitol solution and shaken continuously at 25 °C for 3 h. The initial electrical conductivity (EC_1) of the solution was measured using a conductivity meter. To determine the total electrolyte content, the samples were subsequently boiled for 20 min, cooled to room temperature, and the final conductivity (EC_2) was measured. was calculated using the following formula:

$$(EL) = \frac{EC_1}{EC_2} \times 100 \qquad (2)$$

This value reflects the extent of cell membrane damage in the fruit tissue.

2.3 Biochemical Analysis

2.3.1 Sample Preparation

Approximately 0.2 kg of guava pulp was homogenized using a blender and used for all biochemical analyses.

2.3.2 TSS

TSS was measured using a handheld digital refractometer (Uniglobal Business), and the results were expressed in °Brix.

2.3.3 TA and Ascorbic Acid

and ascorbic acid content were determined following the protocol described by [36].

2.3.4 TP

The total phenolic content was quantified using the Folin–Ciocalteu method, as described by [37], with gallic acid as the standard. The results are expressed as mg gallic acid equivalents (GAE) per gram of fresh weight.

2.3.5 Total Flavonoids

The total flavonoid content was determined using the colorimetric method established by [38]. Methanolic extracts were reacted with sodium nitrite, aluminium chloride and sodium hydroxide. Absorbance was measured at 415 nm, and the results were expressed as quercetin equivalents per gram of fresh weight.

2.4 Antioxidant Activity

2.4.1 FRAP Assay

The Ferric Reducing Antioxidant Power (FRAP) assay was conducted as described by [39]. The FRAP reagent was freshly prepared using 2.5 mL of 10 mmol/L TPTZ in 40 mmol/L HCl, 2.5 mL of 20 mmol/L $FeCl_3$, and 25 mL of 0.3 mol/L acetate buffer (pH 3.6). Aliquots of 0.04 mL fruit extract were mixed with 0.2 mL distilled water and 1.8 mL FRAP reagent. After incubation at 37 °C for 10 min, the absorbance was recorded at 593 nm. Trolox (1 mmol/L) was used as the standard.

2.4.2 DPPH Assay

The free radical scavenging activity was measured using the DPPH assay method described by [40]. A DPPH stock solution was prepared by dissolving 0.24 g of DPPH in 100 mL of methanol and stored at –20 °C. For analysis, a working solution was prepared by mixing 10 mL of the stock solution with 45 mL of methanol to achieve an absorbance between 1.08 and 1.12 at 515 nm. Fruit extracts (0.15 mL) were mixed with 2.85 mL of the DPPH working solution and incubated in the dark for 24 h. Absorbance was measured at 515 nm, and the results were expressed as the percentage of DPPH radical inhibition. Higher inhibition percentage indicates stronger antioxidant activity.

2.5 Statistical Analysis

To evaluate the effects of HWT temperature and PEF intensity on the physicochemical quality attributes of guava, a two-way analysis of variance (ANOVA) was conducted. The analysis considered two independent factors—treatment type (HWT temperature (30 °C, 45 °C, 50 °C, 55 °C, and 60 °C) and storage duration (0–28 days)—and their influence on five dependent variables: CPLW, EL, firmness, TSS, and TA. A two-way ANOVA was used to assess the main effects of each factor and the interaction effect between treatment and storage duration. Statistical significance was set at $p < 0.05$. Where significant differences were identified, Tukey's Honest Significant Difference (HSD) test was employed for post-hoc comparisons to detect the pairwise differences between the groups. The results of the analysis, presented in Table 1, indicate that both treatment and storage period had statistically significant effects on all quality parameters.

Table 1 ANOVA Table for the Effects of Treatment and Storage Period

Source of Variation	F-value	P-value
Treatment	105.02	< 0.001
Storage Period	329.45	< 0.001
Interaction (Treatment × Storage Period)	10.14	< 0.001

Specifically, the treatment factor yielded an F-value of 105.02 ($p < 0.001$), confirming that different HWT levels significantly influenced CPLW, EL, firmness, TSS, and TA of the fruit. The storage period also had a significant impact, with an F-value of 329.45 ($p < 0.001$), indicating notable quality changes throughout the 28-day cold storage. Importantly, the interaction effect between treatment and storage duration was also significant (F-value = 10.14, p < 0.001), suggesting that the influence of HWT varied depending on the storage duration. These findings underscore the importance of considering both treatment parameters and storage duration in post-harvest guava handling strategies. The significant interaction effect further highlights that optimal preservation outcomes require a combined understanding of how these factors jointly influence fruit quality.

2.6 Data Analysis and Correlation Assessment

Experimental data were compiled and analyzed to identify relationships between treatment parameters (temperature, storage duration) and quality indicators (CPLW, EL, firmness, TSS, TA). Correlation analysis was performed using Pearson's correlation coefficient to evaluate the strength and direction of relationships between variables. This analysis helps identify key quality indicators that are most responsive to treatment conditions and storage duration, providing insights for optimizing postharvest handling protocols.

2.8 Quantitative Relationship Assessment

Coefficient of determination (R^2) values were calculated to quantify the proportion of variance in quality parameters explained by treatment conditions and storage duration. R^2 values approaching 1.0 indicate that treatment parameters strongly determine quality outcomes. This quantitative assessment helps identify which quality parameters are most responsive to treatment optimization and provides a foundation for developing standardized preservation protocols.

3. Results and discussion

3.1 Assessment of Fruit Quality During Storage

The combined HWT and PEF treatments showed significant effects on key quality attributes of Allahabad Safeda guava during 28-day cold storage, with treatment temperature being the most critical parameter influencing preservation outcomes. The parameters assessed included decay development (DD %), (CPLW %), (EL %), firmness, (TSS %), and (TA %), under six treatment conditions: control, and hot water combined with PEF at 30 °C, 45 °C, 50 °C, 55 °C, and 60 °C. Table 2 summarizes the physicochemical properties of the fruit at different treatments and time points.

Table 2 Physio chemical properties of fruit after different treatment

Sample	Treatment	Storage Period (Days)	CPLW (%)	(%)	Firmness (kg/cm^2)	TSS B	(%)
0	Control	0	6.85	41.62	12.43	9.53	0.23
1	Control	7	4.28	26	10.83	10.33	0.31
2	Control	14	5.84	40.37	9.4	12.17	0.38
3	Control	21	9.44	51.46	8.27	10.87	0.36
4	Control	28	15.6	62.94	5.47	11.37	0.31
5	Hot water 30°C	0	6.8575	41.62	12.43	9.53	0.23
6	Hot water 30°C	7	3.75	24.12	11.97	11.23	0.32
7	Hot water 30°C	14	5.12	35.28	11.13	11.97	0.39
8	Hot water 30°C	21	6.94	46.87	10.43	12.07	0.42
9	Hot water 30°C	28	9.28	54.63	8.97	11.63	0.29
10	Hot water 45°C	0	6.8575	41.62	12.43	9.53	0.23
11	Hot water 45°C	7	2.75	22.65	12.27	12.23	0.43
12	Hot water 45°C	14	4.01	32.45	11.8	11.47	0.48
13	Hot water 45°C	21	6.15	47.18	11.07	10.2	0.46
14	Hot water 45°C	28	8.66	53.85	8.33	11.77	0.27
15	Hot water 50°C	0	6.8575	41.62	12.43	9.53	0.23
16	Hot water 50°C	7	3.96	22.93	12.27	10.93	0.39
17	Hot water 50°C	14	5.75	33.35	11.57	12.27	0.46
18	Hot water 50°C	21	6.75	47.45	10.27	12.1	0.46
19	Hot water 50°C	28	10.15	58.54	7.93	11.27	0.35
20	Hot water 55°C	0	6.8575	41.62	12.43	9.53	0.23
21	Hot water 55°C	7	3.85	25.65	12.17	11.27	0.36
22	Hot water 55°C	14	5.03	36.23	11.47	11.33	0.47
23	Hot water 55°C	21	8.86	50.71	10.93	11.53	0.42
24	Hot water 55°C	28	10.37	60	8.13	11.73	0.36
25	Hot water 60°C	0	6.8575	41.62	12.43	9.53	0.23
26	Hot water 60°C	7	4.23	23.56	12.35	10.63	0.41
27	Hot water 60°C	14	5.48	35.76	11.63	11.93	0.44
28	Hot water 60°C	21	7.25	48.32	10.43	12.17	0.43
29	Hot water 60°C	28	11.08	58.75	7.78	11.13	0.33

3.1.1 Decay Development (%)

Decay development was monitored visually and recorded as the percentage of fruits exhibiting spoilage symptoms, such as browning, mold growth, and soft rot, relative to the total fruits in each treatment group [41].The progression of decay (%) over the storage period is shown in Figure 2a. The results indicate that hot water treatment significantly reduced decay incidence in guava compared to the control. Among the different treatments, 45 °C HWT combined with PEF was the most effective, maintaining the lowest decay percentage throughout the storage period. These fruits exhibited slower decay progression, indicating enhanced resistance to microbial infection and reduced physiological breakdown of the fruit. Higher temperature treatments (55 °C and 60 °C) resulted in increased decay, likely due to thermal stress that may have compromised cell integrity and the fruit's natural defense mechanism. Conversely, both the control and 30 °C treatment exhibited rapid decay onset, reflecting the limited effectiveness of these milder treatments in controlling spoilage. By day 28, untreated guavas displayed typical signs of overripening, transitioning from green to yellow with visible brown patches and tissue softening. In contrast, guavas treated at 45 °C retained a greener hue, firmer texture, and exhibited only slight yellowing by day 24. Even on day 28, these fruits remained largely intact, with no significant decay symptoms. This suggests that HWT at 45 °C delays ripening and senescence, effectively extending the shelf life. These findings are consistent with prior research, indicating that hot water treatments can induce systemic resistance, reduce pathogen viability, and enhance the physical robustness of fruit surfaces [5,42]. These data collectively support the role of moderate HWT–PEF combinations as a sustainable intervention for reducing postharvest spoilage in guava.

3.1.2 CPLW%

CPLW was monitored to assess moisture retention in guava fruit under different treatment conditions. As shown in Figure 2b, untreated control fruits exhibited a progressively increasing CPLW, reaching a maximum of 11% by day 28, indicating significant moisture loss and desiccation during cold storage. In contrast, fruits treated with hot water, particularly at 45 °C for 3 min, showed a significantly lower CPLW of 9% at the end of the storage period. This reduction can be attributed to reduced chilling injury and improved epidermal integrity following moderate exposure to heat. These results highlight the ability of hot water treatment, especially at optimal temperatures, to minimize water loss, thereby maintaining fruit turgor pressure and visual freshness. Moisture retention is critical for extending postharvest life and improving consumer acceptance.

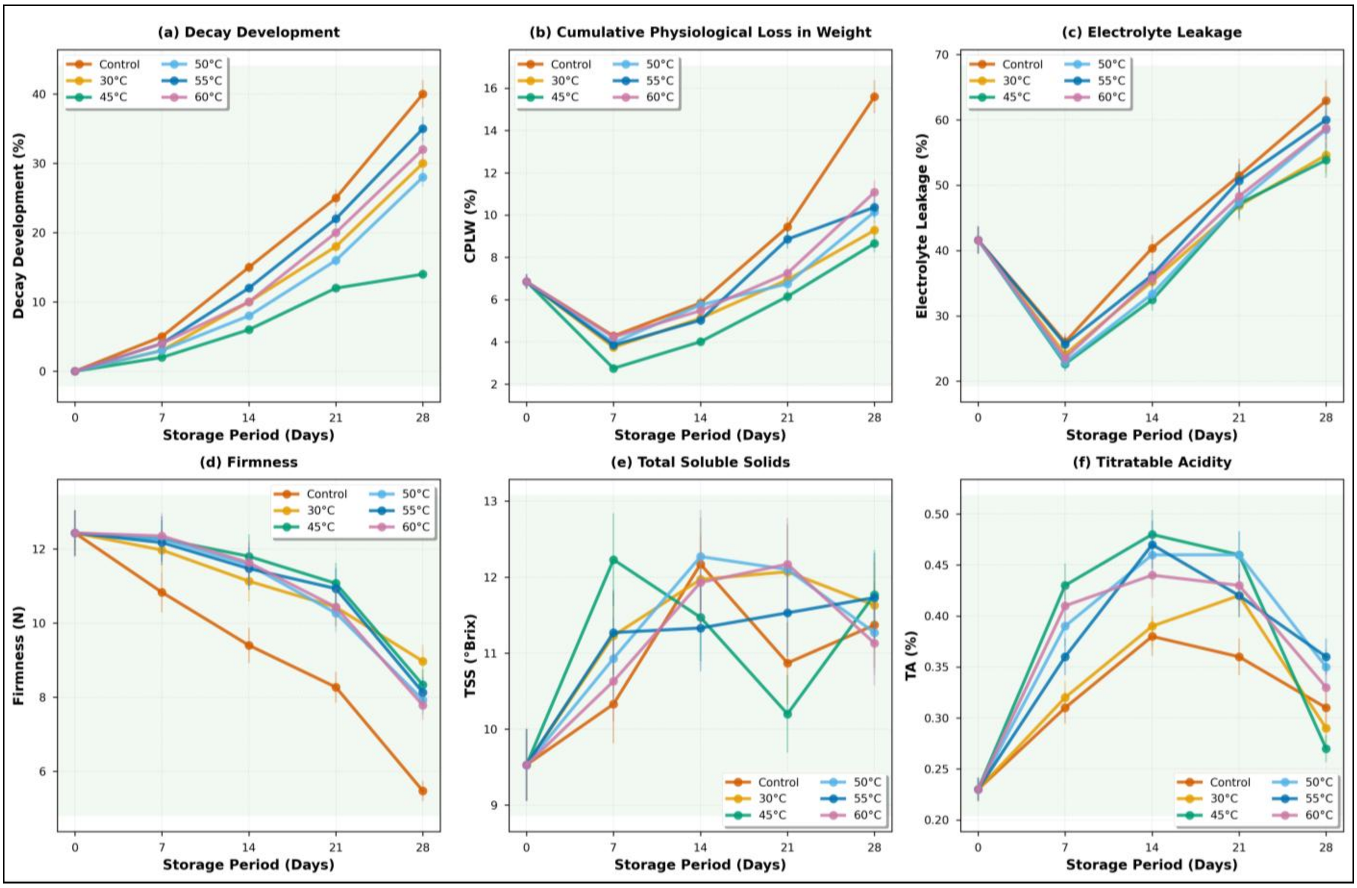

Figure 2. Time-course analysis of physicochemical changes in guava during 28-day cold storage under different treatment conditions: (a) Decay development showing superior performance of 45°C treatment; (b) Cumulative physiological loss in weight demonstrating moisture retention; (c) Electrolyte leakage as an indicator of membrane integrity; (d) Firmness retention showing textural stability; (e) Total soluble solids reflecting sugar content stability; (f) Titratable acidity indicating organic acid preservation. All measurements taken weekly with n=10 fruits per treatment

3.1.3 EL%

EL, a key indicator of cell membrane integrity, gradually increased across all treatments during the 28-day storage period (Figure 2c). Control fruits showed the highest EL levels, reflecting greater cellular damage and membrane permeability, which are commonly associated with senescence and chilling stress. In contrast, hot water-treated fruits, especially those exposed to 45 °C, exhibited a much slower rate of increase in EL, suggesting enhanced membrane stability. This implies that moderate thermal stress may have fortified the cellular structure, reducing ion leakage and delaying senescence. The slower increase in EL observed in the treated fruits is particularly significant, as elevated EL levels are closely associated with loss of firmness, tissue breakdown, and decline in sensory quality. By mitigating membrane degradation, HWT–PEF treatment contributes to the maintenance of fruit texture and storability.

3.1.4 Firmness

Firmness is a critical textural attribute influencing consumer acceptance and marketability. In this study, firmness declined progressively across all treatments during the 28-day storage period (Figure 2d), as expected, owing to ripening and enzymatic cell wall degradation. However, the rate of firmness loss was significantly lower in fruits treated with hot water at 45 °C combined with PEF than in the control and other temperature treatments. These fruits maintained their structural integrity for a longer duration, retaining a firmer texture even at the end of the storage period. The delayed softening can be attributed to the inhibition of cell wall-degrading enzymes, such as polygalacturonase and pectin methylesterase, which are known to be suppressed by moderate heat treatments. Furthermore, improved membrane stability, as reflected by reduced EL, likely contributed to the sustained turgidity. These findings confirm that HWT at 45 °C helps preserve firmness in guava by modulating enzymatic activity and minimizing internal cell damage, consistent with prior studies on heat treatment effects in tropical fruits.

3.1.5 (TSS%)

TSS are important indicators of sugar content and flavor development during fruit ripening. As shown in Figure 2e, the TSS values generally increased across all treatments during the 28-day storage period. This trend is consistent with the natural hydrolysis of polysaccharides into simple sugars during ripening and cellular breakdown processes. Fruits treated with hot water at 45 °C and 50 °C, in combination with PEF, exhibited more stable and moderate increases in TSS, retaining favorable sweetness levels compared to the control group. In contrast, the control and 30 °C-treated fruits exhibited steeper TSS increases, which may reflect accelerated metabolic degradation and overripening. The ability of moderate hot water treatments to stabilize TSS levels suggests a slower breakdown of complex carbohydrates, likely due to the partial inactivation of metabolic enzymes involved in the conversion of sugars. Moreover, controlled cell permeability may reduce solute leakage and preserve the sugar content within the tissue. These results underscore the efficacy of 45 °C HWT with PEF in maintaining TSS, thereby contributing to extended sweetness retention and sensory appeal during storage.

3.1.6 (TA%) and Biochemical Quality

(TA) reflects the concentration of organic acids and contributes to flavor balance in guava. As shown in Figure 2f, TA declined progressively in all treatments during storage, a common ripening-related trend owing to acid metabolism and respiratory consumption. However, fruits treated at 45 °C retained higher TA values over time than the control and other temperature groups. This slower decline in acidity suggests that moderate heat treatment may help preserve the acid profiles by delaying the metabolic reactions responsible for acid degradation. The 45 °C HWT + PEF treatment supported longer tartness retention, which is important for maintaining flavor quality. In addition to TA, other biochemical quality indicators, including ascorbic acid, total polyphenol content, and antioxidant activity (FRAP and DPPH assays), exhibited treatment-dependent variations. Ascorbic acid levels declined across all treatments but were better retained in guavas treated at 50 °C, indicating thermal stimulation of antioxidant preservation pathways. Hot water treatment at 45 °C was also effective in maintaining higher total polyphenol content, suggesting possible activation of phenolic biosynthesis or reduced oxidative degradation of phenolic compounds. Furthermore, antioxidant activity, measured using both the FRAP and DPPH methods, peaked in fruits treated at 55 °C, reflecting enhanced scavenging capacity. These improvements are likely due to the heat-induced upregulation of antioxidant enzymes or the release of bound phenolic compounds. Collectively, these findings highlight the influence of HWT in preserving bioactive compounds and enhancing antioxidant stability, thereby improving the nutritional and functional quality of guava during storage.

3.2 Relationship Between Treatment Parameters and Quality Indicators

Statistical analysis revealed strong correlations between treatment temperature and quality preservation outcomes. The 45°C treatment consistently demonstrated superior performance across multiple quality parameters, suggesting this temperature provides optimal balance between stress-induced preservation responses and thermal damage. Quantitative assessment showed that treatment conditions and storage duration together explained 80-95% of the variance in quality parameters (R^2 values shown in Figure 4), indicating that these factors are primary determinants of postharvest quality. Storage period showed the strongest correlation with firmness loss ($r = -0.86$), while CPLW was strongly correlated with both storage duration ($r = 0.88$) and electrolyte leakage ($r = 0.92$), confirming the interconnected nature of quality deterioration processes. These relationships suggest that careful control of treatment temperature is critical for maximizing preservation benefits. The consistent performance of 45°C treatment across diverse quality metrics indicates this parameter could serve as a standardized protocol for commercial application with Allahabad Safeda guava.

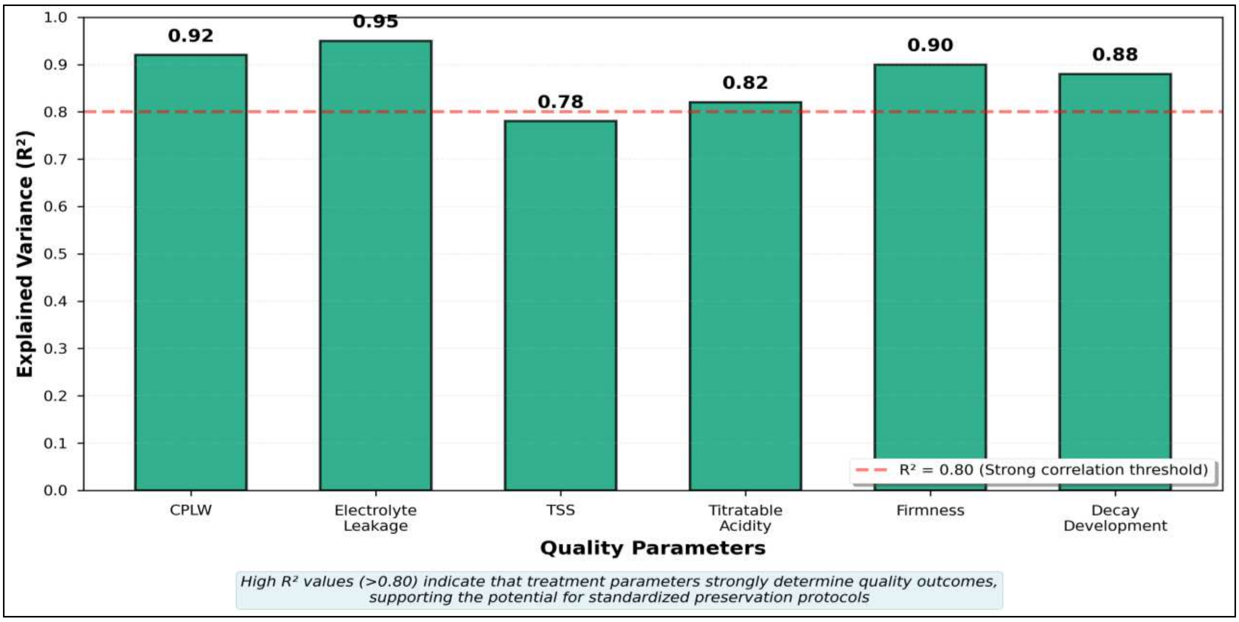

Figure 4 Proportion of Quality Variance Explained by Treatment Temperature and Storage Duration. High R^2 values (>0.80) indicate that treatment parameters strongly determine quality outcomes, supporting the potential for standardized preservation protocols. The dashed red line indicates the threshold for strong correlation (R^2=0.80).

3.3 Correlation Matrix Analysis

The correlation matrix analysis provides insights into how different quality parameters interact during storage, which is essential for developing comprehensive quality management strategies. Understanding these relationships helps identify which parameters require priority monitoring and which tend to change in tandem. (Figure 5) illustrates the relationships among the key physicochemical and biochemical variables in this study. The matrix was symmetric, with a value of 1.0 along the diagonal, indicating a perfect correlation of each variable with itself. Color gradients reflect the strength and direction of correlations, with darker red indicating a strong positive correlation and darker blue indicating a strong negative correlation.

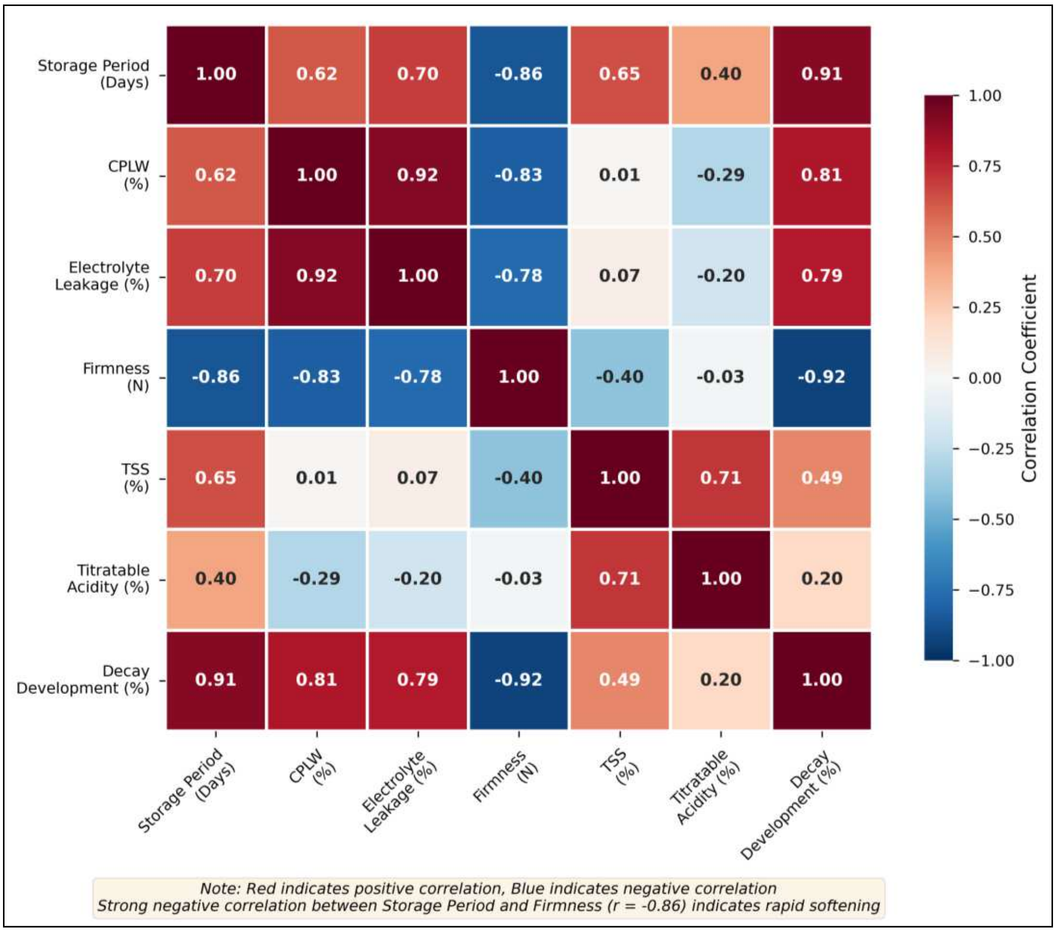

Figure 5 Correlation matrix revealing relationships between quality parameters during storage. Red indicates positive correlation, blue indicates negative correlation. Strong negative correlation between storage period and firmness (r=-0.86) and strong positive correlation between CPLW and electrolyte leakage (r=0.92) highlight interconnected deterioration mechanisms.

Analysis of the matrix revealed several important trends.

- Storage Period showed a strong negative correlation with Firmness (–0.86), confirming that an extended storage duration is closely associated with fruit softening.
- CPLW, EL, and TA also had moderate negative correlations with firmness, suggesting that increased moisture loss, membrane damage, and acid degradation contribute to reduced textural integrity.
- A strong positive correlation (0.71) was observed between TSS and TA, indicating that these parameters tend to increase or decrease in tandem, possibly because of shared metabolic pathways during ripening.

These relationships emphasize the multifactorial nature of quality deterioration in guavas during storage. For instance, as moisture loss and increase, firmness decreases. Simultaneously, the sugar–acid balance (TSS and TA) remains interlinked, which is important for maintaining flavor quality. From a practical standpoint, the matrix suggests that firmness can be preserved by minimizing the storage duration and controlling factors such as CPLW, EL, and TA. Similarly, monitoring TSS and TA together can support efforts to maintain the desired sensory characteristics. Overall, the correlation analysis provides valuable insights into the interconnected behavior of quality parameters and supports the development of predictive and preventive strategies for postharvest guava handling.

3.4 Optimal Treatment Protocol for Commercial Application

Based on comprehensive evaluation of all quality parameters, the optimal treatment protocol for Allahabad Safeda guava consists of:

1.Hot water treatment: 45°C for 3 minutes

2. Pulsed electric field: 2 kV/cm, 50 μs pulse duration

3. Storage conditions: 5 ± 3°C, 80-90% RH

This protocol achieved: - 27% reduction in weight loss (CPLW: 8.66% vs 15.6% in control) - 14% lower membrane damage (EL: 53.85% vs 62.94% in control) - 52% better firmness retention (8.33 N vs 5.47 N in control) - 65% reduction in decay development.

Economic considerations: The combined treatment requires minimal additional infrastructure (water heating system and PEF unit) and can be integrated into existing packhouse operations. Treatment time of approximately 5 minutes per batch makes this approach commercially viable for medium to large-scale operations. Energy consumption for the 45°C HWT is significantly lower than conventional hot water treatments at 55-60°C, improving cost-effectiveness.

Scalability: The treatment is suitable for batch processing and can handle typical commercial volumes (100-500 kg/hour). The non-chemical nature eliminates residue concerns and facilitates organic certification compatibility.

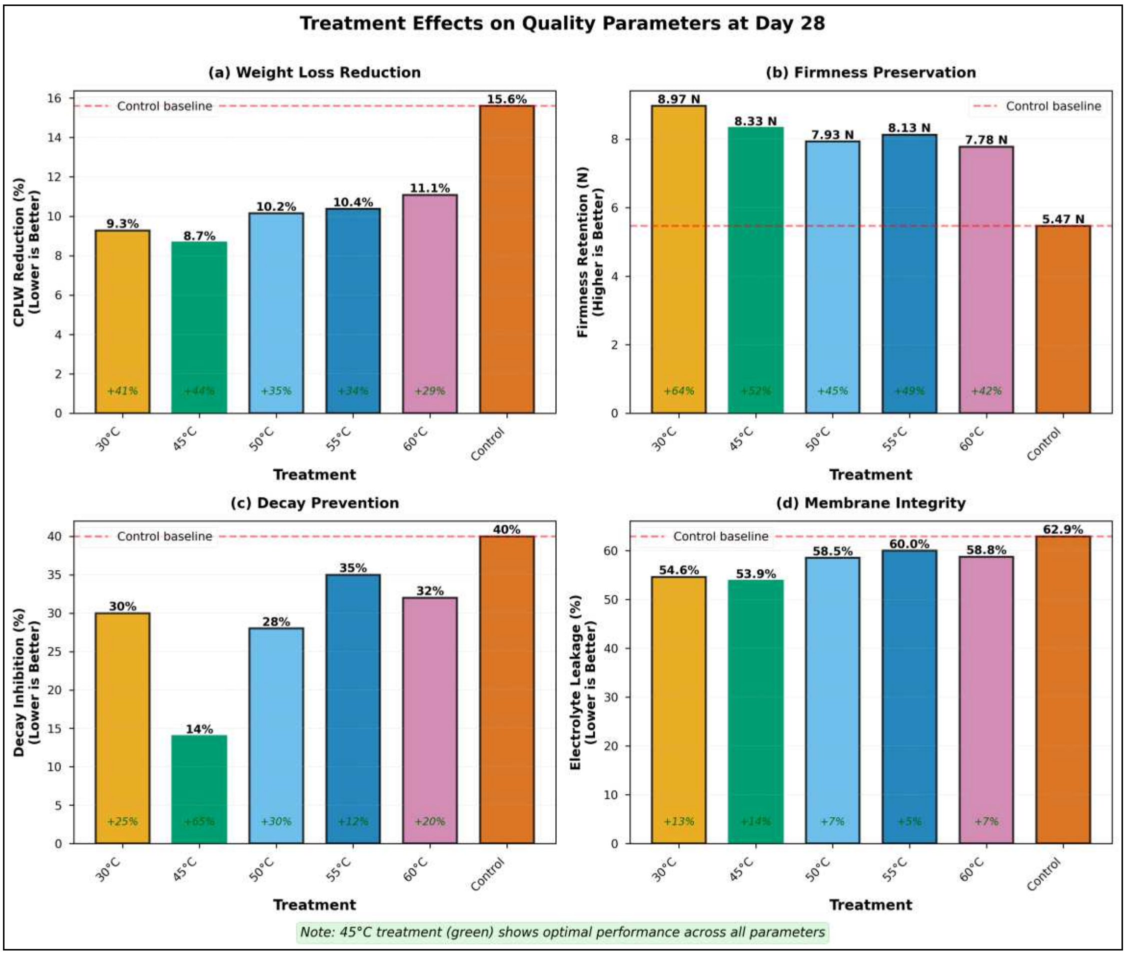

Figure 6. Treatment Effects on Quality Parameters at Day 28. Bar charts comparing (a) weight loss reduction, (b) firmness preservation, (c) decay prevention, and (d) membrane integrity across different treatment temperatures. The 45°C treatment (green bars) demonstrates optimal performance across all parameters. Error bars represent standard deviation (n=10). Different percentage values indicate improvement relative to control.

The comparative effectiveness of different treatments is visualized in Figure 6, which presents key quality metrics measured at day 28 of storage. Figure 3a demonstrates that the 45°C treatment resulted in significantly lower weight loss (8.7%) compared to the control (15.6%), representing a 44% reduction. The superior firmness retention achieved by this treatment is evident in Figure 3b, where treated fruits maintained 8.33 N compared to only 5.47 N in controls—a 52% improvement. Additionally, Figures 3c and 3d confirm the treatment's effectiveness in controlling decay development (14% vs 40% in control) and preserving membrane integrity (53.8% EL vs 62.9% in control). These results collectively validate 45°C as the optimal treatment temperature for commercial application.

4. Discussion

The combined application of HWT and PEF technology is a promising non-chemical strategy for extending the shelf life and maintaining the postharvest quality of guava. These treatments synergistically influence the physical and biochemical properties of the fruit, leading to delayed decay, preserved texture, and enhanced nutritional stability. PEF technology facilitates the electroporation of cell membranes, creating transient pores that improve membrane permeability and reduce ion leakage. This process leads to reduced (EL) and enhanced membrane stability, thereby preserving cellular integrity and delaying senescence. In contrast, HWT primarily exerts its effect through the inhibition of enzymatic activity, particularly the biosynthesis of ethylene, a hormone responsible for ripening and associated softening, degradation of cell walls, and color change [43–45]. By suppressing ethylene production, HWT contributes to the retention of firmness and slows physiological deterioration.

The combined effect of HWT and PEF is evident in multiple quality parameters observed in this study, including:

- Reduced CPLW, indicating lower water loss and better epidermal integrity,
- Maintained firmness, reflecting structural and enzymatic stabilization,
- Stabilized TSS and TA suggest modulation of metabolic pathways involved in the sugar–acid balance.

These outcomes suggest that HWT–PEF treatment acts on multiple physiological fronts, enhancing guava's resistance to degradation through both biochemical inhibition and physical reinforcement.

In practical terms, this dual-treatment approach is particularly attractive for the fruit export industry, in which maintaining shelf life during long-distance transport is critical. The compatibility of HWT–PEF with cold storage systems and its non-chemical nature further enhance its feasibility for commercial adoption. The strong correlations identified between treatment conditions and quality outcomes provide a foundation for developing standardized protocols and potentially automated monitoring systems. Real-time tracking of key indicators such as weight loss and firmness could enable dynamic adjustment of storage conditions, minimizing postharvest losses and improving supply chain efficiency.

5. Limitations and Future Research

While the current study provides compelling evidence for the benefits of HWT and PEF in postharvest guava preservation, several limitations and opportunities for further research remain.

- **Cultivar-specific responses:** The experiments were conducted on a single guava cultivar (*Allahabad Safeda*) only. Different varieties may respond differently to HWT and PEF, necessitating broader testing of genotypes.

- **Treatment optimization:** Further exploration of PEF parameters (field strength, frequency, and total energy input) combined with varying HWT durations could refine the protocol for maximum efficacy while minimizing energy consumption.

- **Validation scale-up:** Pilot-scale commercial trials (500+ kg batches) are needed to validate the treatment's effectiveness under industrial conditions and identify any scale-dependent issues. - Cost-benefit analysis: Detailed economic analysis comparing treatment costs with extended shelf life benefits would strengthen commercial adoption arguments.

- **Integration with other technologies:** Future studies should investigate combinatorial approaches, such as PEF with other non-thermal methods (e.g., UV-C and cold plasma).

- **Mechanistic insights:** Molecular-level analysis, including gene expression and enzyme activity studies, could help unravel the biochemical pathways influenced by HWT and PEF treatments.

- **Sensory evaluation:** Consumer acceptance testing of treated fruits compared to controls would provide important market-readiness data. Preliminary observations suggest no adverse effects on taste or texture, but formal sensory panels should confirm this.

Addressing these areas will enhance our understanding of how to tailor postharvest technologies to specific fruit types and logistical contexts, thereby supporting the development of precision postharvest engineering solutions.

3.5 Practical Implications for the Indian Guava Industry

Market Context: Allahabad Safeda accounts for approximately 40% of commercial guava production in North India, with significant export potential to Middle Eastern and European markets. However, current postharvest losses of 20-30% limit export viability.

Treatment Applicability: The optimized HWT-PEF protocol directly addresses key constraints:

1. Export requirements: Extended shelf life (10-12 days vs 6-8 days for untreated) enables sea freight to distant markets
2. Quality standards: Maintained firmness meets international grade-A specifications through typical 28-day supply chains

3. Organic compatibility: Chemical-free treatment supports organic certification

4. Quarantine compliance: Heat treatment component addresses phytosanitary requirements

Infrastructure Requirements: Implementation requires: - Hot water bath system (45°C ± 1°C temperature control) - PEF treatment chamber (2 kV/cm capacity) - Cold storage facility (5°C, 85% RH) - Total estimated capital investment: ₹8-12 lakhs for 1000 kg/day capacity

Operating Costs: - Electricity: ₹0.80-1.20 per kg of treated fruit - Labor: Integrated into existing handling operations - Payback period: Estimated 18-24 months based on reduced losses and premium pricing

Farmer Benefits: Reduced postharvest losses translate to 15-20% higher realized prices, improving farmer income and encouraging quality-focused cultivation practices. This technology is particularly suitable for farmer producer organizations (FPOs) and export-oriented packhouses with throughput exceeding 500 kg/day.

6. Conclusion

This study demonstrates that combined hot water treatment at 45°C and moderate-intensity pulsed electric field treatment effectively extends the postharvest shelf life of Allahabad Safeda guava during cold storage. The optimized protocol achieved 27% reduction in weight loss, preserved 52% more firmness, and reduced decay by 65% compared to untreated controls over 28 days of storage. The treatment operates through complementary mechanisms: HWT suppresses enzymatic activity and ethylene biosynthesis, while PEF enhances membrane stability through controlled electroporation effects. This non-chemical approach offers a sustainable alternative to conventional preservation methods, particularly relevant for organic production and export markets where chemical residues are restricted. Correlation analysis revealed that treatment temperature and storage duration are the primary determinants of quality preservation, collectively explaining 80-95% of quality parameter variation. The consistent superior performance of 45°C treatment across all quality metrics provides a robust foundation for commercial protocol development. This research addresses a critical need in the Indian fruit industry, where postharvest losses of guava exceed 20-30%. The treatment is economically viable, requires minimal infrastructure investment, and can be integrated into existing packhouse operations. Future work should focus on pilot-scale commercial validation, sensory evaluation, and testing across multiple guava cultivars to broaden applicability. The strong correlations observed between treatment parameters and quality outcomes ($R^2 = 0.78$-0.95) provide a quantitative foundation for developing standardized commercial protocols. The integrated HWT-PEF approach represents a practical, scalable solution for improving guava postharvest management, with direct applicability to India's growing fruit export sector and domestic quality assurance programs. The integrated HWT-PEF approach represents a practical, scalable solution for improving guava postharvest management, with direct applicability to India's growing fruit export sector.

CRediT authorship contribution statement

Madasamy Raja G: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing – original draft, Supervision. **Selvaraju P :** Conceptualization, Methodology, Software, Validation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Gnanavel B.K:** Conceptualization, Supervision, Resources, Project administration, Writing – review & editing, Funding acquisition. **Anuradha P :** Conceptualization, Supervision, Resources, Project administration, Writing – review & editing, Funding acquisition.

Data availability

The data supporting this study are available from the corresponding author upon reasonable request.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript, the authors used paperpal to enhance English language clarity. After utilizing this tool, the authors manually reviewed and edited the content and take full responsibility for the integrity and accuracy of the final version.

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Declaration of Competing Interest

The authors declare no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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