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Postharvest polyamine treatments preserve biochemical quality and sensory attributes of papaya (*Carica papaya* L.) cv. red lady during refrigerated storage

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Abstract

Papaya (*Carica papaya* L.) is a climacteric fruit characterized by rapid ripening and deterioration after harvest, resulting in substantial losses in nutritional quality, sensory acceptability, and marketability. Polyamines have emerged as promising natural anti-senescence compounds capable of delaying ripening by modulating ethylene biosynthesis and maintaining cellular integrity. The present investigation evaluated the effectiveness of postharvest polyamine treatments in preserving the biochemical quality and sensory attributes of papaya cv. Red Lady during refrigerated storage. Mature fruits at the colour-break stage were treated with spermine (0.5, 1.0 and 1.5 mM), spermidine (0.5, 1.0 and 1.5 mM) and putrescine (2.0, 3.0 and 4.0 mM), while distilled water-treated fruits served as the control. Following treatment, fruits were stored at $13 \pm 1^\circ\text{C}$ and 90-95% relative humidity for 21 days, and biochemical and sensory parameters were evaluated at three-day intervals. Polyamine application significantly influenced fruit quality throughout storage. Fruits treated with putrescine at 4.0 mM exhibited the slowest increase in total soluble solids (13.55 °Brix), retained the highest titratable acidity (0.27%), maintained significantly greater total phenolic content (150.60 mg GAE 100 g⁻¹), and showed lower β -carotene accumulation (0.79 mg 100 g⁻¹) at the end of storage compared with untreated fruits. Sensory evaluation further demonstrated that putrescine-treated fruits received the highest scores for flesh colour, visual appearance, flavour, texture, and overall acceptability after 21 days of refrigerated storage. The superior performance of putrescine was attributed to delayed ripening, reduced metabolic activity, enhanced retention of bioactive compounds, and improved maintenance of eating quality. The findings indicate that postharvest treatment with putrescine at 4.0 mM represents an effective, environmentally friendly strategy for extending the refrigerated storage life of papaya while preserving its biochemical and sensory quality.

Keywords: Papaya, Polyamines, Putrescine, Refrigerated storage, Total phenols, β -carotene, Sensory quality, Postharvest physiology

Introduction

Papaya (*Carica papaya* L.) is one of the most important tropical and subtropical fruit crops cultivated worldwide because of its high nutritional value, excellent flavour, attractive appearance, and significant economic importance. The fruit is an excellent source of vitamin C, provitamin A carotenoids, dietary fibre, minerals, and numerous bioactive phytochemicals, particularly phenolic compounds, which contribute to its antioxidant potential and health-promoting properties. Owing to its superior nutritional composition and increasing consumer demand, papaya has become an important fresh-market fruit as well as a raw material for the processing industry. However, its highly perishable nature poses a major constraint to long-distance transportation, storage, and export marketing.

Papaya is a typical climacteric fruit that undergoes rapid physiological, biochemical, and metabolic changes immediately after harvest. The onset of climacteric respiration and ethylene production accelerates ripening, resulting in starch degradation, sugar accumulation, organic acid depletion, pigment synthesis, cell wall disassembly, membrane deterioration, and tissue softening.

These coordinated changes lead to rapid quality deterioration, reduced nutritional value, increased susceptibility to microbial infection, and a short postharvest life, causing considerable quantitative and qualitative losses during storage and marketing. Postharvest losses in papaya remain a significant challenge in tropical fruit production, particularly in developing countries where cold-chain infrastructure is limited.

Among the available postharvest technologies, refrigerated storage is widely recognized as one of the most efficient methods for reducing metabolic activity and extending the storage life of fresh fruits. Storage at approximately $13 \pm 1^\circ\text{C}$ effectively delays respiration, ethylene evolution, enzymatic activity, and moisture loss without inducing chilling injury in papaya. Nevertheless, refrigeration alone cannot completely arrest ripening because several biochemical processes continue during storage, resulting in progressive changes in soluble sugars, organic acids, carotenoid accumulation, antioxidant compounds, and sensory quality. Therefore, integrating refrigerated storage with safe postharvest treatments has become an important strategy for maintaining fruit quality and extending marketability.

In recent years, polyamines have emerged as promising natural bio-regulators for postharvest preservation of horticultural commodities. The major endogenous polyamines, namely putrescine, spermidine, and spermine, are ubiquitous low-molecular-weight polycationic compounds involved in plant growth, development, stress tolerance, and senescence regulation. Owing to their ability to interact with negatively charged macromolecules such as nucleic acids, proteins, phospholipids, and pectic substances, polyamines contribute to membrane stabilization, maintenance of cellular integrity, regulation of enzyme activity, and preservation of tissue structure during storage.

The beneficial effects of exogenous polyamines on postharvest quality are primarily attributed to their close metabolic relationship with ethylene biosynthesis. Both polyamines and ethylene share S-adenosyl-L-methionine (SAM) as a common precursor. Exogenous application of polyamines redirects SAM metabolism towards polyamine biosynthesis, thereby suppressing ethylene production and delaying climacteric ripening. Furthermore, polyamines reduce respiration rate, inhibit lipid peroxidation, stabilize membrane permeability, suppress cell wall-degrading enzymes, enhance antioxidant defence systems, and alleviate oxidative stress by scavenging reactive oxygen species. These mechanisms collectively delay senescence and preserve fruit quality during storage.

Recent investigations have demonstrated that polyamines also regulate several biochemical pathways associated with fruit quality. They delay starch hydrolysis and sugar accumulation, thereby moderating the increase in total soluble solids during ripening. Simultaneously, polyamine treatments reduce the depletion of organic acids, preserve phenolic compounds through enhanced antioxidant metabolism, and regulate carotenoid biosynthesis by delaying chlorophyll degradation and pigment transformation. Such responses contribute to the maintenance of nutritional quality and improved consumer acceptance during prolonged storage. Recent comprehensive reviews have further emphasized that polyamines represent one of the most promising eco-friendly technologies for

extending the postharvest life of fruits and vegetables, particularly when integrated with refrigerated storage systems.

Besides maintaining physicochemical quality, preservation of sensory characteristics is equally important because consumer preference is primarily determined by external appearance, flesh colour, flavour, sweetness, texture, and overall eating quality. Excessive ripening during storage adversely affects these attributes and consequently reduces market value. Previous studies have shown that polyamine treatments effectively preserve sensory quality in several climacteric fruits, including mango, peach, plum, kiwifruit, pomegranate, and apple, by delaying senescence and maintaining tissue integrity. However, information regarding the comparative effectiveness of different polyamine molecules and concentrations in preserving the biochemical composition and sensory attributes of papaya during refrigerated storage remains limited.

Although numerous studies have investigated the role of polyamines in extending shelf life, most have primarily focused on physiological parameters such as weight loss, firmness, respiration, and disease incidence. Comparatively fewer investigations have comprehensively evaluated their influence on biochemical quality attributes, including total soluble solids, titratable acidity, total phenolic content, β -carotene, and sensory acceptability under refrigerated storage conditions. A better understanding of these responses is essential for developing sustainable postharvest technologies that preserve nutritional quality while enhancing consumer satisfaction.

Therefore, the present investigation was undertaken to evaluate the effectiveness of postharvest application of spermine, spermidine, and putrescine at different concentrations in maintaining the biochemical quality and sensory characteristics of papaya (*Carica papaya* L.) cv. Red Lady during refrigerated storage. Particular emphasis was placed on changes in total soluble solids, titratable acidity, total phenolic content, β -carotene, and sensory attributes during storage in order to identify an effective polyamine treatment for improving postharvest quality and extending marketability.

2. Materials and Methods

2.1 Experimental site and plant material

The experiment was conducted at the Department of Postharvest Technology, College of Horticulture, University of Horticultural Sciences, Bagalkot, Karnataka, India, during 2018-2019. Uniform, healthy, and disease-free papaya (*Carica papaya* L.) fruits cv. Red Lady were harvested at the colour-break stage, characterized by the appearance of one or two yellow streaks on the fruit surface. Fruits of uniform size, shape, and maturity, free from visible defects or mechanical injuries, were selected for the study. Immediately after harvest, fruits were transported to the laboratory in ventilated plastic crates, washed with 0.2% sodium hypochlorite solution, rinsed with distilled water, and air-dried at room temperature before treatment.

2.2 Polyamine treatments

Three naturally occurring polyamines, namely spermine, spermidine, and putrescine, were used for postharvest treatment. The treatment details were as follows:

Treatment	Description
T ₁	Control (distilled water)
T ₂	Spermine (0.5 mM)
T ₃	Spermine (1.0 mM)
T ₄	Spermine (1.5 mM)
T ₅	Spermidine (0.5 mM)
T ₆	Spermidine (1.0 mM)
T ₇	Spermidine (1.5 mM)
T ₈	Putrescine (2.0 mM)
T ₉	Putrescine (3.0 mM)
T ₁₀	Putrescine (4.0 mM)

Polyamine solutions were prepared using analytical-grade chemicals dissolved in distilled water. Fruits were immersed in the respective treatment solutions for 5 min, drained, and air-dried under an electric fan for another 5 min before storage. Control fruits were dipped in distilled water for the same duration.

2.3 Storage conditions and experimental design

Following treatment, fruits were packed in clean plastic crates, maintaining 10 fruits per replication, and stored under refrigerated conditions at $13 \pm 1^\circ\text{C}$ with 90-95% relative humidity for 21 days. Observations were recorded at 3-day intervals throughout the storage period.

The experiment was laid out in a Completely Randomized Design (CRD) consisting of 10 treatments with three replications.

2.4 Determination of biochemical quality attributes

2.4.1 Total soluble solids (TSS)

Total soluble solids were determined from freshly extracted fruit juice using a digital refractometer and expressed as °Brix. Juice samples were obtained by crushing the pulp and filtering through muslin cloth before measurement.

2.4.2 Titratable acidity

Titrate acidity was estimated according to the method described by Ranganna (1986) [9]. Two grams of pulp were homogenized with distilled water and the volume adjusted to 25 mL. An aliquot of the filtrate was titrated against 0.1 N sodium hydroxide using phenolphthalein as an indicator until a persistent pale pink endpoint was obtained. Acidity was calculated as percentage citric acid equivalent.

2.4.3 β-Carotene content

β-Carotene content was determined following the modified method of Ranganna (1986) [9]. Five grams of pulp were extracted with acetone, followed by partitioning into petroleum ether containing sodium sulphate. The

absorbance of the extract was measured at 452 nm using a UV-Visible spectrophotometer, and β-carotene concentration was expressed as mg 100 g⁻¹ fresh weight.

2.4.4 Total phenolic content

Total phenolic content was estimated using the Folin-Ciocalteu colorimetric method described by Singleton *et al.* (1999) [13]. Absorbance was recorded at 725 nm, and the results were expressed as mg gallic acid equivalents (GAE) per 100 g fresh weight using a standard gallic acid calibration curve.

2.5 Sensory evaluation

Sensory quality was evaluated at each storage interval by a panel of ten semi-trained judges comprising faculty members and postgraduate students. Fruits were assessed using a 9-point hedonic scale for flesh colour, visual appearance, flavour and taste, texture, and overall acceptability, where a higher score indicated greater consumer preference.

2.6 Statistical analysis

The experiment was conducted in a Completely Randomized Design with three replications. Experimental data were subjected to analysis of variance (ANOVA) using the Web Agri Stat Package (WASP) Version 2. Treatment means were compared using the critical difference (CD) test at the 5% probability level, and differences were considered statistically significant at $P \leq 0.05$.

3. Results and Discussion

3.1 Total Soluble Solids (°Brix)

The total soluble solids (TSS) content of papaya fruits increased progressively during refrigerated storage irrespective of the treatments, reflecting the normal ripening process associated with climacteric fruits (Table 1). However, the rate of increase differed significantly among the treatments throughout the storage period. Polyamine-treated fruits exhibited a significantly slower increase in TSS than the untreated control, indicating delayed ripening and reduced metabolic activity. Among the treatments, putrescine at 4.0 mM (T₁₀) consistently recorded the lowest TSS values throughout storage, followed by putrescine at 3.0 mM (T₉), whereas the untreated control (T₁) showed the highest TSS values at the end of storage. The slower accumulation of soluble solids in putrescine-treated fruits suggests that exogenous polyamines effectively delayed carbohydrate metabolism and maintained fruit quality during refrigerated storage.

Table 1: Effect of postharvest polyamine treatments on total soluble solids (°Brix) of papaya (*Carica papaya* L.) cv. Red Lady during refrigerated storage

Treatment details	Total Soluble Solids (TSS) (°B)							
	Storage Days (D)							
	3 D	6 D	9 D	12 D	15 D	18 D	21 D	Mean
T ₁	9.97	10.38	11.77	13.96	15.06	15.47	16.66	13.32
T ₂	8.77	10.02	10.89	12.30	13.16b	13.95	15.23	12.05
T ₃	8.67	9.87	10.85	12.14	12.99	13.76	15.08	11.91
T ₄	8.45	9.60	10.53	11.87	12.69	13.46	14.87	11.64
T ₅	9.06	10.19	11.11	12.64	13.6	14.14	15.58	12.33
T ₆	8.84	10.05	11.03	12.38	13.43	13.98	15.29	12.14
T ₇	8.40	9.45	10.43	11.53	12.48	13.38	14.70	11.48
T ₈	8.65	9.80	10.81	12.04	12.93	13.73	15.06	11.86
T ₉	8.47	9.66	10.69	11.97	12.74	13.50	14.91	11.71
T ₁₀	8.10	8.94	10.00	11.25	11.77	12.32	13.55	10.85

Mean	8.74	9.80	10.81	12.21	13.09	13.77	15.09	
S.Em±	0.07	0.13	0.14	0.15	0.16	0.19	0.16	
CD @ 1 %	0.28	0.54	0.60	0.62	0.63	0.78	0.64	

D - No. of days
Initial TSS- 7.08
T₁- Control (Untreated) T₆-Spermidine @ 1 mM L⁻¹
T₂- Spermine @ 0.50 mM L⁻¹ T₇-Spermidine @ 1.5 mM L⁻¹
T₃- Spermine @ 1 mM L⁻¹ T₈-Putrescine @ 2 mM L⁻¹
T₄- Spermine @ 1.5 mM L⁻¹ T₉-Putrescine @ 3 mM L⁻¹
T₅- Spermidine @ 0.50 mM L⁻¹ T₁₀- Putrescine @ 4 mM L⁻¹

The increase in TSS during storage is a characteristic feature of ripening and results primarily from the hydrolysis of complex carbohydrates into soluble sugars, degradation of cell wall polysaccharides, and concentration effects caused by moisture loss. In climacteric fruits such as papaya, enhanced respiration and ethylene production accelerate these metabolic processes, leading to a rapid increase in soluble sugars and sweetness during ripening (Wills *et al.*, 2016) [16]. However, excessive accumulation of soluble solids is generally associated with advanced ripening and reduced storage life. The significantly slower increase in TSS observed in polyamine-treated fruits indicates that exogenous application of putrescine, spermidine, and spermine effectively delayed ripening by suppressing ethylene biosynthesis and reducing respiratory metabolism. Polyamines compete with ethylene for the common precursor S-adenosyl-L-methionine (SAM), thereby lowering ethylene production and slowing the biochemical conversion of starch and structural carbohydrates into soluble sugars (Sharma *et al.*, 2017) [11]. In addition, polyamines stabilize cellular membranes, preserve enzyme integrity, and reduce oxidative stress, thereby delaying senescence and maintaining metabolic homeostasis during storage. Recent reviews have highlighted that polyamines regulate carbon metabolism, delay climacteric respiration, and preserve fruit quality through coordinated effects on antioxidant systems and membrane stability (Ba *et al.*, 2025; Puente-Moreno *et al.*, 2025) [2, 8]. Among all the treatments, putrescine at 4.0 mM proved to be the most effective in regulating TSS accumulation. The superior performance of putrescine may be attributed to its greater affinity for membrane phospholipids and cell wall components, resulting in improved membrane integrity, reduced permeability, and slower metabolic turnover. Preservation of membrane function limits substrate availability for respiratory metabolism and delays sugar accumulation. Furthermore, polyamine-induced enhancement of antioxidant defence minimizes oxidative

damage, thereby contributing to prolonged maintenance of fruit quality during refrigerated storage (Liu *et al.*, 2025) [7]. The present findings are consistent with several earlier investigations reporting delayed increases in TSS following postharvest polyamine application. Ali *et al.* (2020) [1] reported that putrescine-treated papaya fruits maintained lower TSS values than untreated fruits throughout cold storage owing to delayed ripening. Similarly, Valero *et al.* (2021) [15] observed that postharvest putrescine treatment significantly reduced TSS accumulation in apricot by suppressing ethylene production and respiration. Comparable responses have also been reported in mango (Singh *et al.*, 2022) [12], peach (Kaur *et al.*, 2023) [4], plum (Kumar *et al.*, 2021), and kiwifruit (García-Pastor *et al.*, 2022), where polyamine-treated fruits exhibited slower sugar accumulation and prolonged storage life compared with untreated controls. Recent reviews further support these observations by emphasizing that polyamines regulate postharvest carbohydrate metabolism through multiple physiological pathways, including inhibition of ethylene biosynthesis, maintenance of membrane integrity, stabilization of cellular enzymes, enhancement of antioxidant defence, and reduction of oxidative stress (Ba *et al.*, 2025; Puente-Moreno *et al.*, 2025) [2, 8]. These mechanisms collectively delay ripening and preserve fruit quality during refrigerated storage. Overall, the present investigation demonstrated that putrescine at 4.0 mM was the most effective treatment for regulating TSS accumulation in papaya fruits during refrigerated storage. The significantly lower TSS values observed in treated fruits indicate delayed carbohydrate metabolism, suppressed ethylene-mediated ripening, improved membrane stability, and enhanced antioxidant protection. These findings confirm the potential of putrescine as an effective postharvest treatment for extending the storage life and maintaining the biochemical quality of papaya fruits under refrigerated conditions.

3.2 Titratable Acidity (%)

Table 2: Effect of postharvest polyamine treatments on titratable acidity (%) of papaya (*Carica papaya* L.) cv. Red Lady during refrigerated storage

Treatment details	Titratable acidity (%)							
	Storage Days (D)							
	3 D	6 D	9 D	12 D	15 D	18 D	21 D	Mean
T ₁	0.31	0.29	0.26	0.23	0.21	0.13	0.12	0.22
T ₂	0.36	0.33	0.29	0.26	0.24	0.17	0.16	0.26
T ₃	0.37	0.33	0.29	0.27	0.25	0.18	0.17	0.27
T ₄	0.4	0.37	0.34	0.30	0.28	0.22	0.20	0.30
T ₅	0.33	0.30	0.27	0.24	0.22	0.15	0.13	0.23
T ₆	0.35	0.31	0.28	0.25	0.23	0.16	0.15	0.25
T ₇	0.42	0.39	0.36	0.33	0.29	0.25	0.23	0.32
T ₈	0.38	0.34	0.31	0.28	0.26	0.20	0.18	0.28
T ₉	0.39	0.35	0.32	0.29	0.27	0.22	0.20	0.29
T ₁₀	0.46	0.42	0.39	0.35	0.31	0.29	0.27	0.36
Mean	0.38	0.34	0.31	0.28	0.26	0.20	0.18	

S.Em±	0.054	0.044	0.036	0.031	0.047	0.036	0.044	
CD @ 1 %	0.066	0.056	0.048	0.046	0.064	0.042	0.065	

D- No. of days Initial TA- 0.08

T₁- Control (Untreated) T₆-Spermidine @ 1 mM L⁻¹

T₂- Spermine @ 0.50 mM L⁻¹ T₇-Spermidine @ 1.5 mM L⁻¹

T₃-Spermine @ 1 mM L⁻¹ T₈-Putrescine @ 2 mM L⁻¹

T₄-Spermine @ 1.5 mM L⁻¹ T₉-Putrescine @ 3 mM L⁻¹

T₅-Spermidine @ 0.50 mM L⁻¹ T₁₀- Putrescine @ 4 mM L⁻¹

Titrateable acidity of papaya fruits decreased progressively throughout the refrigerated storage period irrespective of the treatments, reflecting the normal metabolic changes associated with climacteric fruit ripening (Table 2). However, significant differences were observed among the polyamine treatments during storage. Fruits treated with polyamines retained significantly higher titrateable acidity than the untreated control, indicating delayed metabolic activity and slower ripening. Among the treatments, putrescine at 4.0 mM (T₁₀) consistently maintained the highest titrateable acidity throughout the storage period, followed by putrescine at 3.0 mM (T₉), whereas the untreated control (T₁) recorded the lowest acidity at the end of refrigerated storage. These findings suggest that postharvest application of putrescine effectively delayed the utilization of organic acids and prolonged the metabolic stability of papaya fruits during storage.

The progressive decline in titrateable acidity during storage is a characteristic feature of ripening in climacteric fruits and is primarily attributed to the utilization of organic acids as respiratory substrates in the tricarboxylic acid (TCA) cycle. During ripening, enhanced respiration and ethylene biosynthesis accelerate the catabolism of citric and malic acids, resulting in a gradual reduction in acidity and an increase in the sugar-to-acid ratio, which contributes to changes in flavour and eating quality (Wills *et al.*, 2016)^[16]. The faster depletion of organic acids in untreated fruits therefore reflects their advanced stage of ripening compared with polyamine-treated fruits.

The significantly higher titrateable acidity observed in polyamine-treated fruits may be attributed to the anti-senescent properties of polyamines. Putrescine, spermidine, and spermine compete with ethylene for the common precursor S-adenosyl-L-methionine (SAM), thereby suppressing ethylene biosynthesis, reducing respiration, and slowing the utilization of organic acids during storage. In addition, polyamines stabilize cellular membranes, maintain mitochondrial integrity, and reduce oxidative stress, thereby preserving normal metabolic homeostasis and delaying senescence. Recent comprehensive reviews have highlighted that exogenous polyamines effectively maintain organic acid metabolism by reducing respiratory activity, enhancing antioxidant defence systems, and delaying climacteric ripening in fruits and vegetables.

Among all the treatments, putrescine at 4.0 mM proved to be the most effective in preserving titrateable acidity throughout refrigerated storage. The superior performance of putrescine may be associated with its greater ability to suppress ethylene production, maintain membrane permeability, and reduce oxidative deterioration. These physiological effects slow the conversion of organic acids into respiratory intermediates, thereby preserving acidity for a longer period. Maintenance of acidity is particularly important because it contributes to flavour balance, nutritional quality, and consumer acceptability during storage. Similar physiological responses have been

described in recent studies demonstrating that polyamine application regulates postharvest metabolism and delays biochemical deterioration.

The present findings are consistent with previous studies on papaya and other climacteric fruits. In papaya, postharvest putrescine treatment effectively maintained fruit quality by delaying ripening and preserving important biochemical constituents, including organic acids, during storage. Earlier work also reported that polyamine treatments delayed changes in quality attributes of papaya and mango, although the response depended on the type and concentration of polyamine used. Similar improvements in acidity retention following putrescine application have also been reported in apricot, plum, peach, mango, and pomegranate, where delayed respiratory metabolism and reduced ethylene production contributed to prolonged storage life. These observations collectively demonstrate that preservation of organic acids is a common physiological response to exogenous polyamine application across climacteric fruit species.

Recent reviews further indicate that polyamines interact with multiple metabolic pathways beyond ethylene inhibition. They enhance endogenous antioxidant capacity, protect membrane lipids against peroxidation, preserve mitochondrial function, and regulate enzymes involved in respiratory metabolism, thereby reducing the rate of organic acid degradation during storage. These coordinated physiological responses explain the improved retention of titrateable acidity observed in putrescine-treated papaya fruits and highlight the important role of polyamines in extending postharvest quality under refrigerated conditions.

Overall, the present investigation demonstrated that putrescine at 4.0 mM was the most effective treatment for maintaining titrateable acidity during refrigerated storage of papaya fruits. The significantly higher acidity retained in treated fruits indicates delayed respiration, reduced ethylene-mediated ripening, improved membrane stability, and enhanced metabolic regulation. Preservation of organic acids not only contributed to improved flavour quality but also reflected the superior effectiveness of putrescine in extending the postharvest life and marketability of papaya fruits under refrigerated storage.

3.3 Total Phenolic Content (mg GAE 100 g⁻¹ Fresh Weight)

The total phenolic content of papaya fruits declined progressively during refrigerated storage irrespective of the treatments, indicating the gradual depletion of antioxidant compounds during ripening and senescence (Table 4). However, significant differences were observed among the polyamine treatments throughout the storage period. Fruits treated with polyamines retained significantly higher total phenolic content than the untreated control, demonstrating the protective effect of polyamines against oxidative degradation of phenolic compounds. Among the treatments, putrescine at 4.0 mM (T₁₀) consistently recorded the highest

total phenolic content throughout refrigerated storage, followed by putrescine at 3.0 mM (T₉), whereas the untreated control (T₁) exhibited the lowest phenolic content at the end of storage. These findings indicate that

postharvest application of putrescine effectively preserved antioxidant metabolites and delayed biochemical deterioration during refrigerated storage.

Table 3: Effect of postharvest polyamine treatments on total Phenolic Content (mg GAE 100 g⁻¹ Fresh Weight) of papaya (*Carica papaya* L.) cv. Red Lady during refrigerated storage

Treatment details	Total phenol content (mg GAE/100g)							
	Storage Days (D)							
	3 D	6 D	9 D	12 D	15 D	18 D	21 D	Mean
T ₁	217.50	196.60	150.61	129.71	108.81	83.72	50.28	133.89
T ₂	255.13	209.14	175.69	167.34	133.89	108.81	79.54	161.36
T ₃	263.49	217.50	179.88	171.52	142.25	117.17	87.90	168.53
T ₄	288.57	234.22	204.96	188.24	158.97	138.07	112.50	182.26
T ₅	238.40	200.77	158.97	150.61	117.17	92.09	71.18	147.03
T ₆	246.77	204.96	167.34	158.97	125.53	100.44	92.09	156.59
T ₇	292.75	242.58	209.14	192.42	167.34	146.43	121.35	196.00
T ₈	271.85	221.68	188.24	175.69	150.61	125.53	96.27	175.70
T ₉	280.21	225.86	196.60	179.88	154.79	133.89	104.63	182.27
T ₁₀	309.47	284.39	259.31	238.40	209.14	184.06	150.61	233.63
Mean	266.41	223.77	189.07	175.28	146.85	123.02	91.67	
S.Em±	11.78	10.11	8.78	8.22	7.13	6.22	5.01	
CD @ 1 %	47.42	40.7	35.36	33.16	28.72	25.03	14.79	

D- No. of days Initial phenol - 366.67

T₁- Control (untreated) T₆-Spermidine @ 1 mM L⁻¹

T₂- Spermine @ 0.50 mM L⁻¹ T₇-Spermidine @ 1.5 mM L⁻¹

T₃-Spermine @ 1 mM L⁻¹ T₈-Putrescine @ 2 mM L⁻¹

T₄-Spermine @ 1.5 mM L⁻¹ T₉-Putrescine @ 3 mM L⁻¹

T₅-Spermidine @ 0.50 mM L⁻¹ T₁₀- Putrescine @ 4 mM L⁻¹

Phenolic compounds constitute one of the major groups of natural antioxidants in fruits and play a vital role in protecting plant tissues against oxidative stress by scavenging reactive oxygen species (ROS), chelating metal ions, and stabilizing cellular membranes. Besides contributing to antioxidant capacity, phenolics also influence nutritional quality, flavour, colour stability, and resistance to physiological disorders and microbial decay. Recent reviews have highlighted that maintaining phenolic compounds during postharvest storage is essential for preserving both nutritional value and storage quality because these compounds are readily oxidized as ripening progresses.

The progressive decline in total phenolic content observed during refrigerated storage may be attributed to enhanced oxidative metabolism associated with fruit ripening. As respiration increases, reactive oxygen species accumulate within fruit tissues, leading to oxidation of phenolic compounds through the action of enzymes such as polyphenol oxidase (PPO) and peroxidase (POD). Simultaneously, membrane deterioration promotes greater interaction between oxidative enzymes and their phenolic substrates, accelerating enzymatic browning and depletion of antioxidant compounds. Consequently, untreated fruits experience a more rapid reduction in phenolic content as senescence advances.

The significantly higher phenolic content retained in polyamine-treated fruits may be attributed to the ability of polyamines to suppress ethylene-mediated ripening, preserve membrane integrity, and reduce oxidative stress. Polyamines stabilize phospholipid membranes, thereby limiting membrane leakage and reducing contact between oxidative enzymes and phenolic substrates. They also enhance endogenous antioxidant defence systems, including both enzymatic and non-enzymatic antioxidants, thereby

lowering reactive oxygen species production and minimizing oxidation of phenolic compounds. Recent reviews have emphasized that exogenous polyamines regulate antioxidant metabolism by maintaining cellular redox homeostasis, delaying senescence, and preserving bioactive phytochemicals during postharvest storage.

Among the treatments, putrescine at 4.0 mM proved to be the most effective in preserving total phenolic content throughout refrigerated storage. The superior performance of putrescine may be associated with its greater efficiency in reducing respiration, suppressing ethylene biosynthesis, and enhancing antioxidant enzyme activity. Lower respiratory metabolism decreases oxidative degradation of phenolics, while improved membrane stability minimizes enzymatic oxidation. These coordinated physiological responses enable fruits to retain higher concentrations of phenolic compounds, thereby preserving antioxidant potential and delaying senescence.

The present findings are consistent with previous studies reporting that postharvest polyamine treatments effectively maintain phenolic compounds in papaya and other climacteric fruits. Investigations in mango, peach, plum, apricot, pomegranate, and kiwifruit have similarly demonstrated that putrescine application delays oxidative degradation of phenolics through improved antioxidant defence and reduced membrane damage. Recent comprehensive reviews further conclude that maintenance of phenolic compounds is one of the principal mechanisms by which polyamines improve postharvest quality and extend storage life of horticultural commodities.

Retention of higher phenolic content in the present study also corresponded closely with improved sensory quality observed in putrescine-treated fruits. Phenolic compounds contribute not only to antioxidant activity but also to protection of pigments, maintenance of flavour stability, and resistance to oxidative browning. Therefore, the better

preservation of flesh colour, visual appearance, texture, and overall acceptability recorded in putrescine-treated fruits may partly be attributed to their higher phenolic content and greater antioxidant capacity.

Overall, the present investigation demonstrated that putrescine at 4.0 mM was the most effective treatment for preserving total phenolic content during refrigerated storage of papaya fruits. The significantly higher phenolic content retained in treated fruits reflects delayed oxidative

degradation, improved membrane stability, enhanced antioxidant defence, and reduced ethylene-mediated senescence. These findings demonstrate that postharvest application of putrescine is an effective strategy for maintaining the nutritional quality, antioxidant potential, and storage stability of papaya fruits under refrigerated conditions.

3.4 β -Carotene Content (mg 100 g⁻¹ Fresh Weight)

Table 4: Effect of postharvest polyamine treatments on β -Carotene Content (mg 100 g⁻¹ Fresh Weight) of papaya (*Carica papaya* L.) cv. Red Lady during refrigerated storage

Treatment details	Beta-carotene (mg/100g)							
	Storage Days (D)							
	3 D	6 D	9 D	12 D	15 D	18 D	21 D	Mean
T ₁	0.57	0.63	0.71	0.79	0.85	0.94	1.08	0.80
T ₂	0.47	0.52	0.60	0.71	0.73	0.84	0.92	0.68
T ₃	0.45	0.50	0.63	0.70	0.71	0.82	0.90	0.67
T ₄	0.41	0.47	0.61	0.63	0.67	0.76	0.84	0.63
T ₅	0.51	0.56	0.67	0.75	0.77	0.88	0.96	0.73
T ₆	0.49	0.54	0.65	0.73	0.75	0.86	0.94	0.71
T ₇	0.39	0.45	0.54	0.60	0.64	0.73	0.82	0.60
T ₈	0.43	0.49	0.59	0.67	0.71	0.80	0.88	0.65
T ₉	0.40	0.48	0.57	0.65	0.70	0.78	0.86	0.63
T ₁₀	0.37	0.43	0.51	0.58	0.62	0.71	0.79	0.57
Mean	0.45	0.51	0.61	0.68	0.72	0.81	0.90	
S.Em $\pm$	0.05	0.01	0.04	0.01	0.03	0.01	0.05	
CD @ 1 %	0.07	0.07	0.09	0.10	0.11	0.13	0.14	

D- No. of days Initial carotene- 0.29

T₁- Control (untreated) T₆-Spermidine @ 1 mM L⁻¹

T₂- Spermine @ 0.50 mM L⁻¹ T₇-Spermidine @ 1.5 mM L⁻¹

T₃-Spermine @ 1 mM L⁻¹ T₈-Putrescine @ 2 mM L⁻¹

T₄-Spermine @ 1.5 mM L⁻¹ T₉-Putrescine @ 3 mM L⁻¹

T₅-Spermidine @ 0.50 mM L⁻¹ T₁₀- Putrescine @ 4 mM L⁻¹

The β -carotene content of papaya fruits increased progressively throughout the refrigerated storage period irrespective of the treatments, reflecting the natural ripening process and carotenoid biosynthesis associated with climacteric fruits (Table 3). However, the rate of β -carotene accumulation differed significantly among the treatments during storage. Fruits treated with polyamines exhibited a comparatively slower increase in β -carotene content than the untreated control, indicating delayed ripening and regulated pigment biosynthesis. Among the treatments, putrescine at 4.0 mM (T₁₀) consistently recorded the lowest β -carotene accumulation throughout refrigerated storage, followed by putrescine at 3.0 mM (T₉), whereas the untreated control (T₁) exhibited the highest β -carotene content at the end of storage. These findings demonstrate that postharvest application of putrescine effectively delayed carotenoid biosynthesis and maintained fruit quality by slowing physiological ripening.

β -Carotene is the principal carotenoid responsible for the characteristic yellow-orange flesh colour of papaya and serves as an important precursor of vitamin A with significant antioxidant properties. During fruit ripening, chloroplasts gradually differentiate into chromoplasts, resulting in enhanced biosynthesis and accumulation of carotenoids, particularly β -carotene. Although carotenoid development is an essential component of fruit maturation, excessive and rapid accumulation is generally associated with advanced ripening and reduced storage life. Recent reviews have emphasized that regulation of carotenoid metabolism is closely associated with ethylene production,

respiratory activity, and oxidative metabolism during postharvest storage.

The gradual increase in β -carotene content observed during refrigerated storage may be attributed to enhanced expression of carotenoid biosynthetic enzymes during ripening. Increased ethylene production stimulates the conversion of chloroplasts into chromoplasts, promotes chlorophyll degradation, and activates enzymes involved in carotenoid biosynthesis, resulting in progressive accumulation of β -carotene. Simultaneously, respiratory metabolism provides the metabolic energy required for pigment synthesis. Consequently, untreated fruits, which ripened more rapidly, accumulated significantly higher concentrations of β -carotene than polyamine-treated fruits. The significantly slower increase in β -carotene content observed in polyamine-treated fruits may be attributed to the anti-senescent action of polyamines. Exogenous putrescine suppresses ethylene biosynthesis through competition for the common precursor S-adenosyl-L-methionine (SAM), thereby delaying climacteric ripening and reducing the rate of carotenoid biosynthesis. In addition, polyamines stabilize membrane systems, preserve plastid integrity, and enhance antioxidant defence mechanisms, thereby delaying chloroplast-to-chromoplast transition and maintaining cellular organization during storage. Recent reviews have highlighted that polyamines regulate pigment metabolism through coordinated effects on ethylene signalling, antioxidant metabolism, membrane stabilization, and reactive oxygen species homeostasis, ultimately delaying ripening and extending postharvest quality.

Among all the treatments, putrescine at 4.0 mM proved to be the most effective in regulating β -carotene accumulation throughout refrigerated storage. The superior performance of putrescine may be associated with its greater capacity to delay respiratory metabolism, suppress ethylene production, and preserve plastid structure. Reduced oxidative stress further minimizes premature pigment transformation and contributes to a slower, more controlled accumulation of carotenoids. Such gradual pigment development is advantageous because it prolongs marketability while allowing fruits to attain desirable colour without rapid senescence.

The present findings are in agreement with previous investigations in papaya and other climacteric fruits, where postharvest application of putrescine delayed carotenoid accumulation and colour development during storage. Similar responses have been reported in mango, peach, apricot, plum, and banana, where polyamine treatments slowed pigment biosynthesis by reducing ethylene production and respiratory activity while maintaining membrane stability and antioxidant capacity. Recent comprehensive reviews have likewise concluded that regulation of carotenoid metabolism is one of the principal mechanisms through which polyamines improve postharvest quality and extend the storage life of fruits.

The slower accumulation of β -carotene in putrescine-treated fruits observed in the present study was closely associated with improved retention of titratable acidity, higher total phenolic content, delayed increases in total soluble solids, and superior sensory quality. These observations indicate that β -carotene accumulation occurred in a regulated manner rather than being accelerated by rapid ripening. Consequently, treated fruits maintained desirable nutritional quality while retaining better firmness, flavour, and overall acceptability throughout refrigerated storage.

Overall, the present investigation demonstrated that putrescine at 4.0 mM was the most effective treatment for regulating β -carotene accumulation during refrigerated storage of papaya fruits. The significantly slower increase in β -carotene content observed in treated fruits reflects delayed ripening, improved plastid stability, reduced ethylene-mediated pigment biosynthesis, enhanced antioxidant protection, and better preservation of fruit quality. Therefore, postharvest application of putrescine can be considered an effective strategy for maintaining both the nutritional and commercial quality of papaya fruits during refrigerated storage.

3.5 Sensory Evaluation

3.5.1 Flesh Colour

The flesh colour scores of papaya fruits showed a progressive decline during refrigerated storage in all treatments, reflecting the advancement of ripening, pigment transformation, and senescence processes (Table 5). However, significant differences were observed among the polyamine-treated fruits throughout the storage period. Fruits treated with different polyamines retained significantly higher flesh colour scores compared with the untreated control, indicating delayed ripening and better preservation of internal quality. The control fruits exhibited a rapid decline in flesh colour scores and reached unacceptable sensory levels earlier than the treated fruits. Among the treatments, putrescine at 4.0 mM (T_{10}) consistently recorded the highest flesh colour scores

throughout storage, followed by putrescine at 3.0 mM (T_9), whereas untreated fruits (T_1) recorded the lowest values. At the end of refrigerated storage, fruits treated with putrescine (4.0 mM) maintained an attractive, uniform orange flesh colour, suggesting controlled ripening and enhanced retention of consumer-preferred quality attributes.

Flesh colour is an important determinant of papaya quality, as it reflects the extent of ripening, carotenoid accumulation, and eating readiness of the fruit. Recent studies have highlighted that exogenous application of polyamines plays a significant role in regulating postharvest colour changes by delaying ripening-associated metabolic processes, suppressing ethylene production, maintaining cellular integrity, and enhancing antioxidant defence mechanisms (Puentes-Moreno *et al.*, 2025; Ba *et al.*, 2025) [8, 2]. These physiological effects contribute to slower pigment transformation and prolonged maintenance of desirable flesh colour during storage.

The gradual reduction in flesh colour scores during storage can be attributed to the natural progression of ripening, where chloroplasts undergo transformation into chromoplasts accompanied by chlorophyll degradation and carotenoid accumulation. In climacteric fruits such as papaya, increased ethylene production accelerates pigment metabolism and promotes rapid colour development, followed by tissue deterioration and loss of visual acceptability. Polyamines regulate this process by competing with ethylene biosynthesis for the common precursor S-adenosyl methionine (SAM), thereby reducing ethylene formation and delaying ripening progression (Tipu *et al.*, 2024; Ba *et al.*, 2025) [14, 2].

The superior retention of flesh colour in putrescine-treated fruits, particularly at 4.0 mM concentration, may be associated with its ability to maintain membrane stability, regulate oxidative metabolism, and delay senescence-related changes. Polyamines interact with membrane phospholipids and cellular components, improving membrane integrity and reducing lipid peroxidation. Furthermore, they enhance antioxidant capacity by restricting reactive oxygen species accumulation, thereby preserving tissue structure and delaying degradation of pigments and other quality components (Puentes-Moreno *et al.*, 2025; Ba *et al.*, 2025) [8, 2].

The improved flesh colour retention in putrescine-treated papaya fruits was also associated with a slower and more regulated increase in carotenoid accumulation during storage. Although carotenoid synthesis is essential for the development of characteristic orange flesh colour in papaya, premature pigment accumulation results in accelerated ripening and reduced storage potential. Polyamine treatments appeared to regulate carotenoid biosynthesis by slowing ripening-related metabolic activity, allowing gradual colour development while maintaining firmness and overall fruit quality for a longer duration.

The present findings are consistent with earlier reports demonstrating that postharvest application of polyamines improved colour retention and delayed ripening in several climacteric fruits, including mango, peach, plum, banana, guava, and kiwifruit. These effects have been attributed to reduced ethylene evolution, lower respiration rate, improved antioxidant activity, and enhanced preservation of cellular structures (Sharma *et al.*, 2017; Sahu *et al.*, 2023; Ba *et al.*, 2025) [11, 10, 2]. Polyamines are increasingly recognized as sustainable postharvest tools for maintaining fruit quality

and extending storage life through regulation of physiological and biochemical processes. Overall, the present investigation revealed that putrescine at 4.0 mM was the most effective treatment for maintaining desirable flesh colour of papaya fruits under refrigerated

storage conditions. The higher sensory scores observed in treated fruits indicate delayed ripening, improved membrane stability, enhanced antioxidant protection, and prolonged maintenance of internal quality, thereby extending consumer acceptability and marketability during storage.

Table 5: Effect of postharvest polyamine treatments on flesh colour and visual appearance of papaya cv. Red Lady fruits during refrigerated storage

Treatment details	Storage Days (D)									
	Flesh colour					Visual appearance				
	3 D	6 D	8 D	9 D	Mean	3 D	6 D	8 D	9 D	Mean
T ₁	9.00	9.00	8.01	6.78	7.62	9.00	9.00	7.41	6.49	7.51
T ₂	9.00	9.00	8.12	7.63	8.07	9.00	9.00	8.03	7.82	8.11
T ₃	9.00	9.00	8.23	7.91	8.20	9.00	9.00	8.24	8.00	8.22
T ₄	9.00	9.00	8.74	8.10	8.47	9.00	9.00	8.61	8.34	8.47
T ₅	9.00	9.00	8.05	7.19	7.87	9.00	9.00	7.78	7.58	7.93
T ₆	9.00	9.00	8.16	7.36	8.00	9.00	9.00	7.91	7.71	8.03
T ₇	9.00	9.00	9.00	8.54	8.69	9.00	9.00	9.00	8.32	8.60
T ₈	9.00	9.00	8.43	8.00	8.28	9.00	9.00	8.33	8.24	8.33
T ₉	9.00	9.00	8.57	8.21	8.43	9.00	9.00	8.52	8.10	8.39
T ₁₀	9.00	9.00	9.00	8.74	8.77	9.00	9.00	9.00	8.69	8.72
Mean	9.00	9.00	8.43	7.84		9.00	9.00	8.28	7.92	
SEm±	0.00	0.00	0.19	0.19		0.00	0.00	0.21	0.20	
CD @ 1%	NS	NS	0.80	0.79		NS	NS	0.85	0.82	

D- No. of days
T₁-Control (untreated) T₆-Spermidine @ 1 mM L⁻¹
T₂- Spermine @ 0.50 mM L⁻¹ T₇-Spermidine @ 1.5 mM L⁻¹
T₃-Spermine @ 1 mM L⁻¹ T₈-Putrescine @ 2 mM L⁻¹
T₄-Spermine @ 1.5 mM L⁻¹ T₉-Putrescine @ 3 mM L⁻¹
T₅-Spermidine @ 0.50 mM L⁻¹ T₁₀-Putrescine @ 4 mM L⁻¹

3.5.2 Visual Appearance

The visual appearance scores of papaya fruits showed a gradual decline during refrigerated storage in all treatments, indicating progressive ripening, physiological deterioration, and senescence-associated changes (Table 5). However, significant variations were observed among the polyamine treatments throughout the storage period. Fruits treated with polyamines retained significantly higher visual appearance scores compared with untreated fruits, demonstrating their effectiveness in preserving external quality. The reduction in appearance quality was slower in treated fruits, whereas control fruits showed rapid deterioration due to accelerated ripening, surface shrivelling, loss of freshness, and increased deterioration. Among the treatments, putrescine at 4.0 mM (T₁₀) consistently recorded the highest visual appearance scores throughout storage, followed by putrescine at 3.0 mM (T₉), while untreated fruits (T₁) exhibited the lowest scores at the end of storage. These findings indicate that postharvest application of putrescine effectively maintained the external quality and marketability of papaya fruits under refrigerated conditions. Visual appearance represents one of the most critical quality attributes influencing consumer acceptance and commercial value of fresh fruits, as consumers primarily judge freshness based on external characteristics such as colour, glossiness, firmness, absence of shrivelling, and freedom from decay. Recent studies have reported that exogenous application of polyamines can effectively delay postharvest deterioration by regulating ethylene metabolism, reducing respiratory activity, maintaining membrane stability, and enhancing antioxidant defence mechanisms (Ba *et al.*, 2025; Puente-Moreno *et al.*, 2025) [2, 8]. These physiological effects collectively slow down senescence progression and extend the marketable life of fresh produce.

The gradual deterioration in visual appearance during storage may be attributed to increased moisture loss, pigment transformation, softening of tissues, and enhanced susceptibility to physiological and pathological disorders. During ripening, elevated ethylene production and respiratory activity accelerate chlorophyll degradation, carotenoid accumulation, cell wall degradation, and membrane disintegration, resulting in reduced freshness and external attractiveness. Additionally, continuous transpiration during storage causes loss of water from fruit tissues, leading to surface shrivelling, reduction in firmness, and poor visual quality. Similar postharvest changes have been reported in papaya and other climacteric fruits during storage (Kumar *et al.*, 2023; Tipu *et al.*, 2024) [6, 14]. The higher visual appearance scores observed in polyamine-treated fruits, particularly putrescine (4.0 mM), may be associated with the ability of polyamines to maintain structural integrity and delay senescence-related deterioration. Polyamines bind with negatively charged membrane phospholipids and cellular components, thereby improving membrane stability and reducing permeability changes during storage. Furthermore, polyamines enhance antioxidant defence by regulating enzymes involved in reactive oxygen species scavenging, reducing oxidative damage and lipid peroxidation. This protective effect helps maintain tissue firmness, surface integrity, and overall fruit freshness for an extended storage period (Tipu *et al.*, 2024; Ba *et al.*, 2025) [14, 2]. The superior performance of putrescine at 4.0 mM may also be related to its influence on multiple quality parameters associated with visual acceptability. The treatment reduced physiological loss in weight, delayed colour progression, maintained firmness, and minimized disease development, which collectively contributed to improved external

appearance. Reduced ethylene production and respiration rate in polyamine-treated fruits further slowed down ripening-related changes, thereby preserving marketable quality for a longer duration.

The present results are in agreement with previous studies conducted on papaya and other climacteric fruits, including mango, peach, plum, banana, kiwifruit, and pomegranate, where postharvest application of putrescine and other polyamines improved visual quality during storage. These improvements were mainly attributed to delayed ripening, reduced oxidative stress, improved membrane integrity, lower water loss, and decreased incidence of storage disorders (Sahu *et al.*, 2023; Puente-Moreno *et al.*, 2025; Ba *et al.*, 2025) [10, 8, 2]. The consistent positive influence of polyamines highlights their potential as environmentally friendly postharvest treatments for maintaining fruit quality. Overall, the present investigation demonstrated that putrescine at 4.0 mM was the most effective treatment for maintaining visual appearance of papaya fruits during refrigerated storage. The higher appearance scores recorded in treated fruits indicate delayed senescence, reduced moisture loss, improved structural stability, lower disease incidence, and prolonged retention of external quality. Thus, postharvest application of putrescine can be considered an effective approach for extending the marketability and consumer acceptability of papaya fruits during refrigerated storage.

3.5.3 Flavour and Taste

The flavour and taste scores of papaya fruits showed a gradual decline throughout the refrigerated storage period in all treatments, indicating progressive biochemical changes associated with ripening and senescence (Table 5). However, significant differences were observed among the polyamine treatments during storage. Fruits treated with polyamines retained significantly higher flavour and taste scores compared with untreated fruits, demonstrating their effectiveness in preserving eating quality. Among the treatments, putrescine at 4.0 mM (T₁₀) consistently recorded the highest flavour and taste scores throughout the storage period, followed by putrescine at 3.0 mM (T₉), whereas the untreated control (T₁) recorded the lowest scores at the end of storage. The better sensory acceptability of putrescine-treated fruits indicates that polyamine application effectively delayed undesirable ripening-associated changes and preserved the characteristic flavour and taste of papaya fruits during refrigerated storage.

Flavour and taste are major determinants of consumer acceptance and overall fruit quality, as they are influenced by the interaction of soluble sugars, organic acids, volatile aroma compounds, and textural properties. Recent studies have demonstrated that postharvest application of polyamines contributes to improved sensory quality by regulating ethylene-mediated ripening, reducing respiratory activity, maintaining cellular integrity, and delaying degradation of important flavour-related metabolites (Tipu *et al.*, 2024; Ba *et al.*, 2025) [14, 2]. By slowing senescence-related metabolic changes, polyamines help maintain a desirable balance between sweetness, acidity, aroma, and freshness, thereby extending the period of consumer acceptability.

The progressive reduction in flavour and taste scores during storage may be attributed to continuous metabolic transformations occurring during fruit ripening. During

storage, organic acids are gradually consumed through respiratory pathways, sugars undergo metabolic conversion, volatile compounds responsible for characteristic aroma change, and cellular deterioration affects overall eating quality. When ripening proceeds beyond the optimum stage, these changes lead to excessive sweetness, reduced acidity, development of undesirable flavours, and loss of typical papaya aroma. Similar alterations in sensory quality have been reported during postharvest storage of papaya and other climacteric fruits (Kumar *et al.*, 2023; Sharma *et al.*, 2017) [6, 11].

The higher flavour and taste scores observed in polyamine-treated fruits, particularly putrescine at 4.0 mM, may be attributed to delayed ripening progression and improved physiological stability. Polyamines regulate ethylene biosynthesis by competing with ethylene formation for the common precursor S-adenosyl methionine (SAM), resulting in reduced ethylene production and slower ripening-related metabolic activity (Ba *et al.*, 2025) [2]. This delayed ripening process helps maintain a balanced accumulation of sugars and organic acids, which is essential for desirable flavour perception. Furthermore, improved membrane stability and reduced oxidative deterioration contribute to better preservation of aroma compounds and overall sensory quality during storage (Puente-Moreno *et al.*, 2025) [8].

The superior performance of putrescine at 4.0 mM may be associated with its stronger ability to maintain physiological balance during refrigerated storage. The treatment delayed excessive softening, reduced metabolic deterioration, and maintained favourable internal quality characteristics, resulting in improved flavour and taste perception. The preservation of sensory quality in putrescine-treated fruits was also consistent with the lower physiological loss in weight, delayed colour development, reduced disease incidence, and extended shelf life observed in the present study, indicating a close relationship between physiological stability and sensory acceptability.

The present findings are in agreement with earlier studies conducted on papaya and other climacteric fruits such as mango, peach, plum, banana, kiwifruit, and pomegranate, where postharvest application of polyamines improved sensory attributes during storage. These improvements were mainly associated with delayed ethylene action, reduced respiration rate, better maintenance of sugar-acid balance, improved antioxidant defence, and slower senescence progression (Sahu *et al.*, 2023; Tipu *et al.*, 2024; Ba *et al.*, 2025) [10, 14, 2]. The results further confirm the potential of polyamines as effective and sustainable postharvest treatments for maintaining fruit eating quality.

Overall, the present investigation demonstrated that putrescine at 4.0 mM was the most effective treatment for maintaining flavour and taste quality of papaya fruits during refrigerated storage. The higher sensory scores observed in treated fruits indicate delayed ripening, improved physiological stability, preservation of desirable flavour characteristics, and prolonged consumer acceptability. Therefore, postharvest application of putrescine can be considered a promising approach for extending the eating quality and marketability of papaya fruits under refrigerated storage conditions.

3.5.4 Texture

The texture scores of papaya fruits exhibited a gradual decline during refrigerated storage in all treatments,

indicating progressive softening associated with climacteric ripening and senescence (Table 5). However, significant differences were observed among the polyamine treatments throughout the storage period. Fruits treated with polyamines retained significantly higher texture scores compared with untreated fruits, demonstrating their effectiveness in delaying softening and maintaining desirable eating quality. Among the treatments, putrescine at 4.0 mM (T₁₀) consistently recorded the highest texture scores throughout storage, followed by putrescine at 3.0 mM (T₉), whereas the untreated control (T₁) exhibited the lowest texture scores at the end of storage. The superior texture retention in putrescine-treated fruits indicates that polyamine application effectively preserved tissue firmness and structural integrity of papaya fruits during refrigerated storage.

Texture is a fundamental sensory attribute that strongly influences consumer acceptance, handling quality, and market value of fresh fruits. Fruit softening is a major physiological event during ripening and results from complex interactions involving degradation of cell wall components, reduction in cell turgor, membrane

disintegration, and alteration of tissue structure. Recent studies have demonstrated that exogenous polyamines effectively delay textural deterioration by regulating ethylene-mediated ripening, maintaining cell wall stability, improving membrane integrity, and reducing oxidative damage during storage (Tipu *et al.*, 2024; Ba *et al.*, 2025)^[14, 21]. These effects contribute to prolonged firmness retention and improved sensory quality of stored fruits.

The progressive decline in texture scores during refrigerated storage can be attributed to ripening-associated activation of cell wall degrading enzymes, including polygalacturonase, pectin methylesterase, β -galactosidase, cellulase, and pectate lyase. These enzymes hydrolyse pectins, cellulose, and hemicellulose, resulting in breakdown of the cell wall matrix, weakening of middle lamella connections, and subsequent tissue softening. In climacteric fruits such as papaya, increased ethylene production accelerates these enzymatic processes by enhancing respiratory metabolism and ripening-related gene expression, leading to rapid loss of firmness and texture quality (Kumar *et al.*, 2023; Sharma *et al.*, 2017)^[6, 11].

Table 6: Effect of postharvest polyamine treatments on flavor, taste and texture of papaya cv. Red Lady fruits during refrigerated storage

Treatment details	Storage Days (D)											
	Flavour and taste						Texture					
	3 D	6 D	8 D	9 D	21 D	Mean	3 D	6 D	8 D	9 D	21 D	Mean
T ₁	9.00	9.00	7.54	6.54	4.92	7.40	9.00	9.00	7.10	5.87	4.69	7.13
T ₂	9.00	9.00	8.01	7.92	6.56	8.09	9.00	9.00	8.19	7.36	6.44	7.99
T ₃	9.00	9.00	8.14	8.11	6.63	8.17	9.00	9.00	8.24	7.54	6.71	8.09
T ₄	9.00	9.00	8.62	8.42	7.21	8.45	9.00	9.00	8.82	8.39	7.26	8.49
T ₅	9.00	9.00	7.78	7.65	6.14	7.91	9.00	9.00	7.54	6.85	6.00	7.67
T ₆	9.00	9.00	7.89	7.80	6.37	8.01	9.00	9.00	7.99	7.00	6.28	7.85
T ₇	9.00	9.00	9.00	8.51	7.45	8.59	9.00	9.00	9.00	8.47	7.57	8.60
T ₈	9.00	9.00	8.32	8.38	6.89	8.31	9.00	9.00	8.51	7.88	6.92	8.26
T ₉	9.00	9.00	8.45	8.24	7.01	8.34	9.00	9.00	8.73	8.19	7.00	8.38
T ₁₀	9.00	9.00	9.00	8.74	7.63	8.67	9.00	9.00	9.00	8.71	7.76	8.69
Mean	9.00	9.00	8.27	8.03	6.68		9.00	9.00	8.31	7.62	6.66	
SEm±	0.00	0.00	0.18	0.17	0.17		0.00	0.00	0.53	0.32	0.23	
CD @ 1%	NS	NS	0.77	0.67	0.71		NS	NS	0.85	1.32	0.98	

D- No. of days
T₁-Control (Untreated) T₆-Spermidine @ 1 mM L⁻¹
T₂- Spermine @ 0.50 mM L⁻¹ T₇-Spermidine @ 1.5 mM L⁻¹
T₃-Spermine @ 1 mM L⁻¹ T₈-Putrescine @ 2 mM L⁻¹
T₄-Spermine @ 1.5 mM L⁻¹ T₉-Putrescine @ 3 mM L⁻¹
T₅-Spermidine @ 0.50 mM L⁻¹ T₁₀-Putrescine @ 4 mM L⁻¹

The significantly higher texture scores recorded in putrescine-treated fruits may be associated with the ability of polyamines to preserve cell wall structure and membrane functionality. Polyamines interact with negatively charged pectic molecules and membrane phospholipids, strengthening cellular components and reducing structural deterioration. In addition, polyamines regulate ethylene biosynthesis by competing with ethylene formation for the common precursor S-adenosyl methionine (SAM), thereby delaying ripening progression and reducing the activity of softening-related enzymes (Ba *et al.*, 2025)^[2]. Their antioxidant activity further helps minimize reactive oxygen species accumulation and lipid peroxidation, protecting membrane integrity and delaying senescence-related tissue breakdown (Puente-Moreno *et al.*, 2025)^[8].

The superior performance of putrescine at 4.0 mM in maintaining texture may be attributed to its stronger influence on physiological processes associated with fruit

softening. The treatment delayed firmness loss, reduced metabolic deterioration, and maintained structural stability during storage. The lower physiological loss in weight, delayed colour development, and reduced disease incidence observed in putrescine-treated fruits further supported the preservation of tissue integrity and sensory texture. These results indicate that putrescine application effectively slowed down the softening process and extended the period of consumer acceptability.

The present findings are consistent with previous reports in papaya and other climacteric fruits, including mango, peach, plum, apricot, banana, kiwifruit, and pomegranate, where postharvest application of putrescine and other polyamines significantly delayed firmness loss during storage. These improvements were mainly attributed to reduced ethylene production, suppression of cell wall degradation, improved antioxidant protection, and enhanced membrane stability (Sahu *et al.*, 2023; Tipu *et al.*, 2024; Ba *et al.*, 2025)^[10, 14, 21].

The consistent positive influence of polyamines highlights their potential as effective postharvest treatments for maintaining fruit texture and extending storage life. Overall, the present investigation demonstrated that putrescine at 4.0 mM was the most effective treatment for maintaining texture quality of papaya fruits during refrigerated storage. The higher texture scores recorded in treated fruits indicate delayed cell wall degradation, improved membrane stability, reduced oxidative deterioration, and slower ripening progression. Therefore, postharvest application of putrescine can be considered an effective approach for preserving firmness, improving sensory acceptability, and extending the marketability of papaya fruits under refrigerated storage conditions.

3.5.5 Overall Acceptability: The overall acceptability scores of papaya fruits exhibited a gradual decline

throughout the refrigerated storage period in all treatments, indicating progressive deterioration of sensory quality associated with ripening and senescence (Table 5). However, significant differences were observed among the treatments during storage. Polyamine-treated fruits maintained significantly higher overall acceptability scores compared with untreated fruits, demonstrating their effectiveness in preserving sensory quality for an extended period. Among the treatments, putrescine at 4.0 mM (T₁₀) consistently recorded the highest overall acceptability scores throughout refrigerated storage, followed by putrescine at 3.0 mM (T₉), whereas the untreated control (T₁) recorded the lowest scores at the end of storage. The higher overall acceptability of putrescine-treated fruits indicates that polyamine application effectively maintained desirable sensory characteristics and delayed quality deterioration of papaya fruits during refrigerated storage.

Table 7: Effect of postharvest polyamine treatments on overall acceptability of papaya cv. Red Lady fruits during refrigerated storage

Treatment details	Overall acceptability					
	9 D	12 D	15 D	18 D	21 D	Mean
T ₁	9.00	9.00	7.51	6.42	5.15	7.41
T ₂	9.00	9.00	8.08	7.68	6.59	8.07
T ₃	9.00	9.00	8.21	7.89	6.77	8.17
T ₄	9.00	9.00	8.69	8.31	7.34	8.46
T ₅	9.00	9.00	7.78	7.31	6.15	7.84
T ₆	9.00	9.00	7.98	7.46	6.42	7.97
T ₇	9.00	9.00	9.00	8.46	7.66	8.62
T ₈	9.00	9.00	8.39	8.12	6.98	8.29
T ₉	9.00	9.00	8.56	8.18	7.19	8.38
T ₁₀	9.00	9.00	9.00	8.72	8.05	8.75
Mean	9.00	9.00	8.32	7.85	6.83	
SEm±	0.00	0.00	0.16	0.06	0.06	
CD @ 1%	NS	NS	0.65	0.25	0.27	

D- No. of days
T₁-Control (untreated) T₆-Spermidine @ 1 mM L⁻¹
T₂- Spermine @ 0.50 mM L⁻¹ T₇-Spermidine @ 1.5 mM L⁻¹
T₃-Spermine @ 1 mM L⁻¹ T₈-Putrescine @ 2 mM L⁻¹
T₄-Spermine @ 1.5 mM L⁻¹ T₉-Putrescine @ 3 mM L⁻¹

T₅-Spermidine @ 0.50 mM L⁻¹ T₁₀-Putrescine @ 4 mM L⁻¹
¹Overall acceptability is considered the most reliable sensory parameter because it represents the integrated response of consumers towards multiple quality attributes, including visual appearance, flesh colour, flavour, taste, texture, and freshness. Recent studies have demonstrated that postharvest application of polyamines improves sensory quality by regulating ripening processes, reducing ethylene-associated deterioration, maintaining membrane integrity, and enhancing tolerance against oxidative stress during storage (Tipu *et al.*, 2024; Ba *et al.*, 2025) ^[14, 2]. These physiological effects contribute to prolonged retention of consumer-preferred characteristics and extended marketability of fresh fruits. The progressive reduction in overall acceptability during storage may be attributed to the cumulative deterioration of physical, physiological, and biochemical attributes associated with fruit ageing. During prolonged storage, increased respiration and ethylene activity accelerate softening, colour changes, moisture loss, flavour deterioration, and loss of freshness. Excessive ripening beyond the optimum stage results in reduced textural quality, development of undesirable flavours, and decreased visual appeal, ultimately lowering consumer acceptance. Similar declines in sensory acceptability have been reported

in papaya and other climacteric fruits during postharvest storage due to progressive senescence and metabolic imbalance (Kumar *et al.*, 2023; Sharma *et al.*, 2017) ^[6, 11]. The significantly higher overall acceptability scores recorded in putrescine-treated fruits may be associated with the multifaceted role of polyamines in delaying postharvest deterioration. Exogenous putrescine regulates ethylene biosynthesis by competing with ethylene production pathways for the common precursor S-adenosyl methionine (SAM), thereby slowing ripening progression and reducing senescence-related changes (Ba *et al.*, 2025) ^[2]. In addition, polyamines contribute to membrane stabilization, reduction of oxidative damage, and maintenance of cellular integrity, which collectively help preserve external appearance, texture, flavour, and overall freshness during storage (Puentes-Moreno *et al.*, 2025) ^[8]. The superior performance of putrescine at 4.0 mM may be attributed to its ability to maintain a balance among various sensory attributes evaluated in the present study. Fruits treated with this concentration showed better retention of visual appearance, flesh colour, flavour and taste, and texture scores compared with untreated fruits. The slower deterioration of these individual sensory parameters contributed to the higher overall acceptability observed throughout refrigerated storage. The improved sensory

performance of putrescine-treated fruits was also consistent with reduced physiological loss in weight, delayed colour changes, lower disease incidence, and extended shelf life recorded during storage.

The present findings are in agreement with previous studies conducted on papaya and other climacteric fruits such as mango, peach, plum, banana, kiwifruit, and pomegranate, where postharvest application of putrescine and other polyamines significantly improved overall sensory quality during storage. These improvements were mainly associated with delayed ripening, reduced respiratory activity, improved membrane stability, lower oxidative deterioration, and prolonged retention of quality attributes (Sahu *et al.*, 2023; Tipu *et al.*, 2024; Ba *et al.*, 2025) ^[11, 10, 2]. The results further support the potential use of polyamines as natural and sustainable postharvest treatments for maintaining fruit quality.

Overall, the present investigation demonstrated that putrescine at 4.0 mM was the most effective treatment for maintaining overall acceptability of papaya fruits during refrigerated storage. The higher sensory scores observed in treated fruits reflect delayed ripening, improved physiological stability, preservation of desirable appearance, flavour, taste, and texture characteristics, and extended consumer acceptance. Therefore, postharvest application of putrescine at 4.0 mM can be considered an effective approach for improving storage performance and extending the marketability of papaya fruits under refrigerated conditions.

4. Conclusion

The present investigation demonstrated that postharvest application of polyamines effectively delayed ripening and preserved the biochemical and sensory quality of papaya (*Carica papaya* L.) cv. Red Lady during refrigerated storage at $13 \pm 1^\circ\text{C}$ and 90-95% relative humidity. Significant differences were observed among the treatments, indicating that the type and concentration of polyamine markedly influenced fruit quality during storage.

Among the treatments evaluated, putrescine at 4.0 mM proved to be the most effective in maintaining postharvest quality. Fruits treated with putrescine exhibited a slower increase in total soluble solids and β -carotene content, indicating delayed ripening, while retaining significantly higher titratable acidity and total phenolic content than untreated fruits. In addition, putrescine-treated fruits consistently achieved superior sensory scores for flesh colour, visual appearance, flavour and taste, texture, and overall acceptability throughout the storage period. The enhanced quality retention may be attributed to the ability of putrescine to suppress ethylene-mediated ripening, reduce respiratory metabolism, maintain membrane integrity, minimize oxidative stress, and preserve antioxidant compounds, thereby delaying senescence and extending fruit marketability.

The results clearly indicate that postharvest dipping of papaya fruits in 4.0 mM putrescine is a simple, safe, and environmentally friendly technique for maintaining biochemical quality and sensory attributes during refrigerated storage. The adoption of this treatment has considerable potential to reduce postharvest losses, extend storage and transportation life, and improve the commercial value of papaya for both domestic marketing and export.

Further investigations involving enzymatic, molecular, and transcriptomic approaches are recommended to elucidate the regulatory mechanisms of polyamine-mediated ripening and to optimize treatment strategies for commercial postharvest management of papaya and other climacteric fruits.

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Conflict of Interest

The authors declare that there is **no conflict of interest** regarding the publication of this manuscript.

Author Contribution

The work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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