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RESEARCH ARTICLE

Post-harvest strategies to enhance storage life and quality of banana leaves (*Musa* spp.) intended for eco-friendly food packaging applications

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Abstract

Banana leaves (*Musa* spp.) are widely used as eco-friendly disposable plates and biodegradable packaging material for wrapping food items, jasmine flowers and religious offerings (prasad) in Hindu temples of South India. However, their commercial utilisation for these purposes is limited by rapid post-harvest deterioration. The present study aimed to evaluate the effects of different post-harvest treatments on the shelf life and quality attributes of banana leaves cv. Chakkai Peyan. The experiment was conducted in a completely randomised design (CRD) comprising 14 treatments under two storage environments: ambient and cold storage (5 ± 2 °C). The results revealed that physiological loss in weight (PLW %), chlorophyll degradation, tensile strength reduction, freshness decline and yellowness increased progressively during storage across all treatments. Among the treatments, ascorbic acid + 6-benzylaminopurine (BAP) each at 1 % under cold storage at 5 ± 2 °C (T_8) was the most effective, recording the lowest PLW (17.30 %), highest chlorophyll retention (22.60 SPAD), maximum tensile strength (1.35 N mm^{-2}), superior freshness score (3.00), leaf yellowing and the longest shelf life (16.5 days). Treatments involving individual application of ascorbic acid or BAP under cold storage were statistically comparable to the optimised treatment (T_8). In contrast, the untreated control under ambient conditions showed the poorest performance, with a shelf life of only 4.3 days. The study concludes that integrating suitable post-harvest treatments with cold storage significantly improves banana leaf storage life and quality, enhancing its sustainable packaging potential.

Keywords: banana leaves; biodegradable; cytokinin; post-harvest; senescence; storage life; sustainable packaging

Introduction

Banana (*Musa* spp.) is an important food crop ranking as the fourth most vital staple food in the world after rice, wheat and maize. It is considered a highly versatile crop due to the utility of all its anatomical components. Banana leaves constitute a major proportion of the above-ground biomass and are widely used as eco-friendly biodegradable food packaging materials. However, their rapid post-harvest deterioration limits their storage life and commercial utilisation. Therefore, developing effective post-harvest strategies to maintain leaf quality and extend storage life is essential. India, China, Indonesia, Nigeria, Ecuador, Brazil, Philippines, Angola and Guatemala account for nearly 70 % of global banana production, with global production expected to increase marginally by approximately 1 % annually. India is the largest producer of bananas and shares 16.41 % of the global banana production (1). Banana leaves, though often considered a by-product of banana cultivation, possess considerable cultural, industrial and economic importance.

The large surface area, flexibility and natural waxy coating make them highly suitable for traditional applications such as serving food. This practice holds strong cultural significance in many South Asian countries. In addition to their traditional use as serving plates, banana leaves are widely utilised as natural food wrappers in several societies due to their distinctive aroma, flavour and symbolic value (2). The growing concern about environmental pollution caused by single-use plastics has renewed interest in banana leaves as a sustainable, biodegradable alternative. Their larger size, thickness and foldability make them a practical substitute for plastic-based food packaging materials (3). The demand for fresh banana leaves is rising, but their shelf life is shorter. Recently, banana leaves have been increasingly exported in bulk from India to meet growing international demand. Hence, it is imperative to develop advanced post-harvest protocols to maintain their freshness for longer periods to meet the demand in the domestic as well as international markets. Meticulous handling is required to improve the shelf life. The quality and retention of freshness in banana leaves are based on

several factors viz., the genetic nature, harvesting time, season of harvest, storage temperature and post-harvest physiological changes.

Post-harvest treatments play a crucial role in maintaining leaf quality and extending shelf life. Antioxidants such as ascorbic acid help scavenge reactive oxygen species and reduce chlorophyll degradation (4), while 6-benzylaminopurine (BAP) delays senescence by preserving chlorophyll and metabolic activity (5). Glycerine acts as a humectant, reducing moisture loss and maintaining leaf turgidity (6), whereas citric acid inhibits enzymatic browning by lowering pH (7). Previous studies have demonstrated that pre-treatments can improve the shelf life and quality attributes of banana leaves intended for packaging applications. However, comparative information on the effectiveness of selected chemical treatments and their combinations in maintaining the storage stability, turgidity and functional quality of banana leaves remains limited (8, 9).

Banana leaves have a short shelf life due to high post-harvest temperatures that accelerate metabolic activity and senescence. Storage temperature is a key factor influencing post-harvest quality, with low-temperature storage reducing physiological weight loss, maintaining freshness and prolonging usability compared to ambient conditions. Optimal storage temperatures ranging from 5–10 °C have been reported to effectively extend shelf life, whereas lower temperatures may induce chilling injury (10–13). Rapid removal of field heat through precooling further reduces metabolic rates and extends storage life. Water immersion, as a precooling method, helps maintain fresh weight and relative water content

However, limited information is available regarding the post-harvest handling and storage management of banana leaves, particularly for locally important cultivars. Among the different banana cultivars, cv. Chakkai Peyan is mainly cultivated for leaves in parts of South India and is commonly preferred for leaf utilisation due to its large leaf size and suitability for food serving purposes. Understanding the post-harvest behaviour of banana leaves of this cultivar under different treatments is important for developing suitable storage strategies. Therefore, the present study was undertaken to evaluate the effect of different post-harvest treatments on physiological weight loss, chlorophyll retention, tensile strength, freshness of leaf, leaf colour and overall shelf life of banana leaves (*Musa* spp. cv. Chakkai Peyan) during storage.

Materials and Methods

The experiment was conducted at the Department of Fruit Science, Horticultural College and Research Institute, Coimbatore, Tamil Nadu, from November to December 2025. The experiment was laid out in a completely randomised design (CRD) consisting of 14 treatments (Table 1) with 3 replications.

Freshly harvested banana leaves of uniform maturity and size were collected from healthy plants of banana cultivar Chakkai Peyan. Leaves free from physical damage and disease symptoms were selected for the study. The leaves were cut into a round, plate-like shape and washed with tap water, except for the control leaves. Each treatment consisted of a stack of 5 leaves per replication. The banana leaves were immersed for 30 min in different solutions, namely cold water, ascorbic acid (1 %), BAP (1 %), citric acid (1 %) and glycerine (1 %) as per the treatment specifications. After treatment, the banana leaves were stored under two different conditions, namely ambient and cold storage. The leaves were monitored daily for changes in quality attributes until they became unsuitable for use.

Parameters recorded

Physiological loss in weight

Physiological loss in weight (PLW) was determined by recording the initial weight of the leaves and comparing it with the weight recorded during the storage period using an electronic analytical balance (Giritronics Pvt. Ltd.) (14). The PLW was calculated using the following formula:

$$PLW(\%) = \frac{W_1 - W_2}{W_1} \times 100 \quad \text{Eq. (1)}$$

where:

W_1= Initial weight (g)

W_2= Final weight (g)

Tensile strength

The tensile strength test was performed to determine the tensile strength of banana leaf samples. Leaf strips measuring 25 mm in width and 100 mm in length were tested using a texture analyser (TA Plus, Lloyd Instruments Ltd., UK). The samples were clamped between two pegs with a 1 kN load cell, operated at a crosshead speed of 100 mm min^{-1} with a 0.5 N preload. Tests were conducted at room temperature and the mean of 6 replications was recorded (12).

Table 1. Treatment details

Treatment notations	Treatments
T_1	Cold water treatment (20 ° C) + ambient storage (28 ± 2 °C)
T_2	Cold water treatment (20 ° C) + cold storage (5 ± 2 °C)
T_3	Ascorbic acid at 1 % + ambient storage (28 ± 2 °C)
T_4	Ascorbic acid at 1 % + cold storage (5 ± 2 °C)
T_5	6-Benzyl aminopurine (BAP) at 1 % + ambient storage (28 ± 2 °C)
T_6	BAP at 1 % + cold storage (5 ± 2 °C)
T_7	Ascorbic acid at 1 % + BAP at 1 % + ambient storage (28 ± 2 °C)
T_8	Ascorbic acid at 1 % + BAP at 1 % + cold storage (5 ± 2 °C)
T_9	Citric acid at 1 % + ambient storage (28 ± 2 °C)
T_{10}	Citric acid at 1 % + cold storage (5 ± 2 °C)
T_{11}	Glycerin at 1 % + ambient storage (28 ± 2 °C)
T_{12}	Glycerin at 1 % + cold storage (5 ± 2 °C)
T_{13}	Without pre-treatment (Control) + ambient storage (28 ± 2 °C)
T_{14}	Without pre-treatment (Control) + cold storage (5 ± 2 °C)

Tensile strength was expressed as N mm^{-2} using the formula :

$$TS = \frac{p}{(txb)} \quad \text{Eq. (2)}$$

p = the breaking force or maximum tensile load applied to the sample, measured in newtons (N).

t = the thickness of the sample, measured in millimetres (mm).

b = the breadth/width of the sample, measured in millimetres (mm).

Chlorophyll content

Chlorophyll content was measured using a portable SPAD-502 chlorophyll meter (Konica Minolta, Tokyo, Japan). The SPAD readings were recorded from the central portion of the banana leaf lamina at regular intervals during storage. About 10 observations were taken for each treatment and the mean value was calculated.

Visual evaluation

Leaf freshness score: Freshness of the leaves was evaluated visually using a scoring scale based on appearance, texture and overall acceptability. The score was assigned based on the degree of wilting and loss of turgidity. Freshness was assessed using a 5-point rating scale, where 5 = extremely fresh/excellent, 4 = fresh/good quality with minor defects, 3 = fair/slightly to moderately objectionable defects, 2 = unfresh/poor quality with excessive defects and 1 = extremely poor quality/declined. The leaves were considered acceptable when the freshness score was above 3 (12).

Leaf colour: The degree of leaf colour change from green to yellowing in banana leaves during storage was assessed using a visual rating scale. The score indicated the extent of chlorophyll degradation and the colour change from green to yellow. Leaf colour was evaluated using a 5-point scale, where 1 = dark green, 2 = light green, 3 = yellowish-green, 4 = greenish-yellow and 5 = yellow. The leaves were considered acceptable when the leaf colour score was less than 3 (12).

Shelf life

Shelf life was defined as the number of days for which banana leaves remained acceptable for use. Leaves were considered unacceptable when the freshness score fell below 3 and/or the leaf colour score exceeded 3.

Statistical analysis

The experimental data were analysed using R software (Version 2026.01.1+403). Analysis of variance (ANOVA), appropriate for a CRD was performed to assess the significance of treatment effects. Whenever significant differences among treatments were observed, treatment means were separated using Fisher's least significant difference (LSD) test at the 5 % level of significance ($p \leq 0.05$). The results are presented as treatment means along with standard error of mean [SE(m) ±], critical difference (CD) at $p = 0.05$ and coefficient of variation (CV %). Different lowercase letters accompanying treatment means indicate significant differences among treatments.

Results and Discussion

Physiological loss in weight

Physiological loss in weight increased significantly ($p < 0.05$) with storage duration across all treatments, indicating continuous moisture loss and metabolic activity. Significant differences among treatments were observed due to the combined effects of pre-treatments and storage environments. In general, treated leaves stored under cold storage (5 ± 2 °C), particularly those receiving post-harvest pretreatments, recorded lower PLW (%) than those under ambient conditions, indicating that the combined effect of the treatments and low-temperature storage effectively reduced moisture loss and delayed senescence. Among the treatments, T_8 (ascorbic acid + BAP each at 1 % + cold storage) recorded the lowest PLW % throughout the storage period (2.33 % at 3 days after pretreatments (DAP) and 17.30 % at 18 DAP), indicating superior moisture retention. This was followed by T_4 (6.60 % at 3 DAP and 20.34 % at 18 DAP) and T_6 (5.58 % at 3 DAP and 21.55 % at 18 DAP), which also maintained relatively low PLW %. In contrast, the highest PLW % was recorded in T_{14} (9.12 % at 3 DAP and 29.08 % at 18 DAP), followed by T_2 and T_{12}, indicating greater moisture loss in less effective treatments. This is reflected by the absence of PLW values beyond 6 DAP in these treatments, indicating rapid deterioration under ambient storage. In contrast, cold storage treatments-maintained leaf quality for up to 18 days (Fig. 1). The complete mean values and statistical groupings for PLW (%) at each storage interval are provided in Supplementary Table 1. The lower PLW % observed under cold storage can be attributed to reduced vapour pressure deficit and slower physiological processes, which minimise transpiration and respiration losses. The superior performance of T_8 may be due to the synergistic effect of ascorbic acid and BAP, where ascorbic acid acts as an antioxidant by scavenging reactive oxygen species and stabilising cell membranes, while BAP delays senescence by maintaining cellular metabolism. In contrast, higher PLW % and reduced shelf life under ambient conditions may be attributed to elevated temperature, which accelerates moisture loss and metabolic activity. Similar findings have been reported by earlier workers, who observed that low-temperature storage significantly reduces physiological weight loss and prolongs freshness compared to ambient conditions (15–17).

Chlorophyll content

Chlorophyll content declined progressively during storage across all treatments, indicating advancement of senescence, with significant differences ($p < 0.05$) among treatments due to the combined effects of pre-treatments and storage environments. In general, leaves stored under cold storage (5 ± 2 °C) retained higher chlorophyll content compared to those under ambient conditions. Among the treatments, T_8 (ascorbic acid + BAP each at 1 % + cold storage) recorded the highest chlorophyll content (31.20 initially and 22.60 at 18 DAP), indicating effective delay in chlorophyll degradation. This was followed by T_6 (29.10 initially and 21.40 at 18 DAP) and T_4 (25.90 initially and 16.20 at 18 DAP), which also maintained comparatively higher chlorophyll levels. In contrast, the lowest chlorophyll content was recorded in T_{12} (21.10 initially and 14.30 at 18 DAP) and control treatment T_{14}, indicating rapid pigment degradation (Fig. 2). The complete mean values and statistical groupings for chlorophyll content at each storage interval are provided in Supplementary Table 2. Ambient treatments were evaluated only up to 6 DAP due to rapid senescence. The higher chlorophyll retention observed in T_8 may be attributed to the synergistic effect of BAP and ascorbic acid under low-temperature storage. 6-benzylaminopurine delays leaf senescence by inhibiting chlorophyll-degrading enzymes such as chlorophyllase and pheophytinase, reducing the activity of oxidative enzymes including polyphenol oxidase and lipoxygenase and maintaining chloroplast integrity. Meanwhile, ascorbic acid protects chlorophyll pigments from oxidative damage by scavenging reactive oxygen species, thereby contributing to prolonged leaf greenness

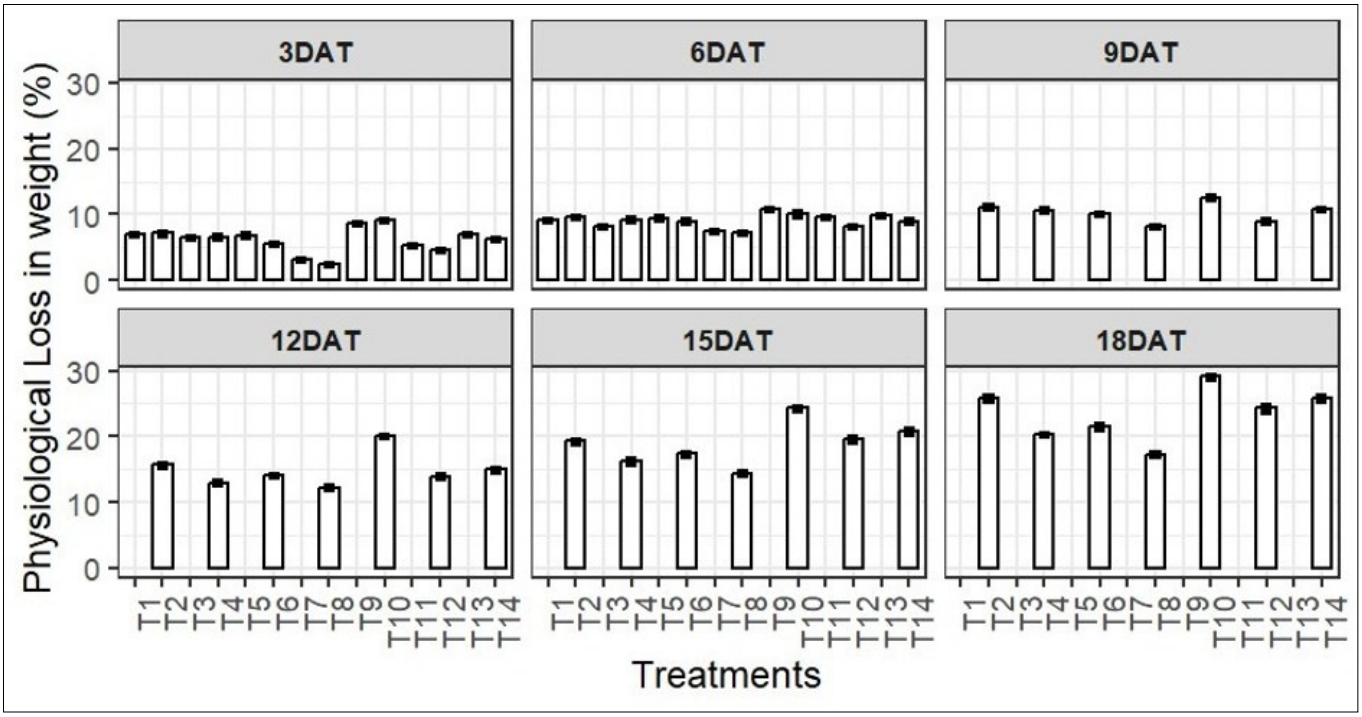


Fig. 1. Effect of post-harvest treatments on physiological loss in weight (%) during storage.

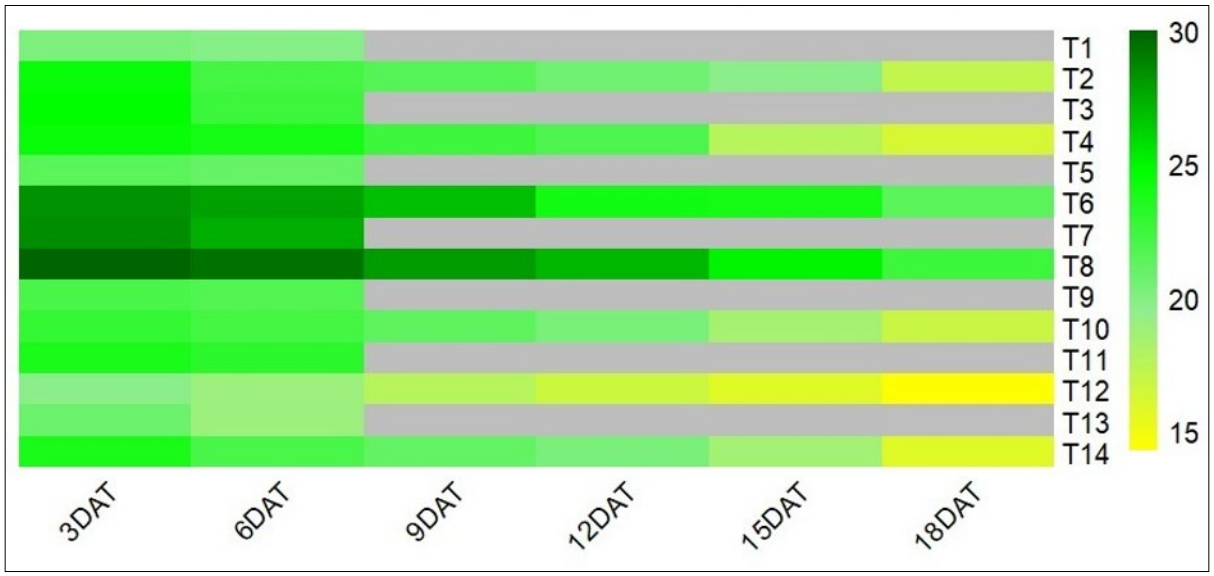


Fig. 2. Heatmap representation of chlorophyll (SPAD Units) of banana leaves under different treatments during storage conditions.

and quality during storage. Cold storage further slows respiration and enzymatic activity, thereby preserving chlorophyll. In contrast, rapid chlorophyll degradation under ambient conditions may be due to increased oxidative stress, enhanced chlorophyllase activity and accelerated senescence (18, 19).

Tensile strength

Tensile strength decreased significantly ($p < 0.05$) with storage duration across all treatments, indicating progressive loss of structural integrity due to ageing and moisture depletion. Significant variation among treatments was observed due to the combined effects of pre-treatments and storage environments, with cold storage (5 ± 2 °C) maintaining higher tensile strength than ambient storage throughout the storage period. Among the treatments, T_8 (ascorbic acid + BAP each at 1 % under cold storage) exhibited the greatest retention of tensile strength, recording 9.60 N mm^{-2} at 3 DAP and maintaining 1.35 N mm^{-2} at 18 DAP. This was followed by T_{10} (9.05 N mm^{-2} at 3 DAP and 1.08 N mm^{-2} at 18 DAP) and T_6 (7.30 N mm^{-2} at 3 DAP and 1.01 N mm^{-2} at 18 DAP), which also maintained tensile strength for a longer duration. In contrast, T_{12} recorded lower tensile strength values (7.56 N mm^{-2} at 3 DAP and 0.78 N mm^{-2} at 18 DAP), indicating a greater loss of mechanical integrity during storage. Control treatments maintained acceptable tensile strength only for a shorter period during storage, reflecting faster structural deterioration of the leaves (Fig. 3). The complete mean values and statistical groupings for tensile strength at each storage interval are provided in Supplementary Table 3. Ambient treatments were evaluated only up to 4–6 days due to rapid senescence. The higher tensile strength observed in T_8 may be attributed to better preservation of cell wall components and tissue hydration. The combined effect of ascorbic acid and BAP helps maintain the integrity of structural polysaccharides such as cellulose and hemicellulose, while cold storage slows enzymatic degradation and metabolic activity. In contrast, untreated leaves under ambient conditions undergo rapid degradation of cell wall materials due to increased metabolic activity, resulting in reduced mechanical strength and early tissue breakdown. Similar observations have been reported in plant tissues under post-harvest storage (20, 21).

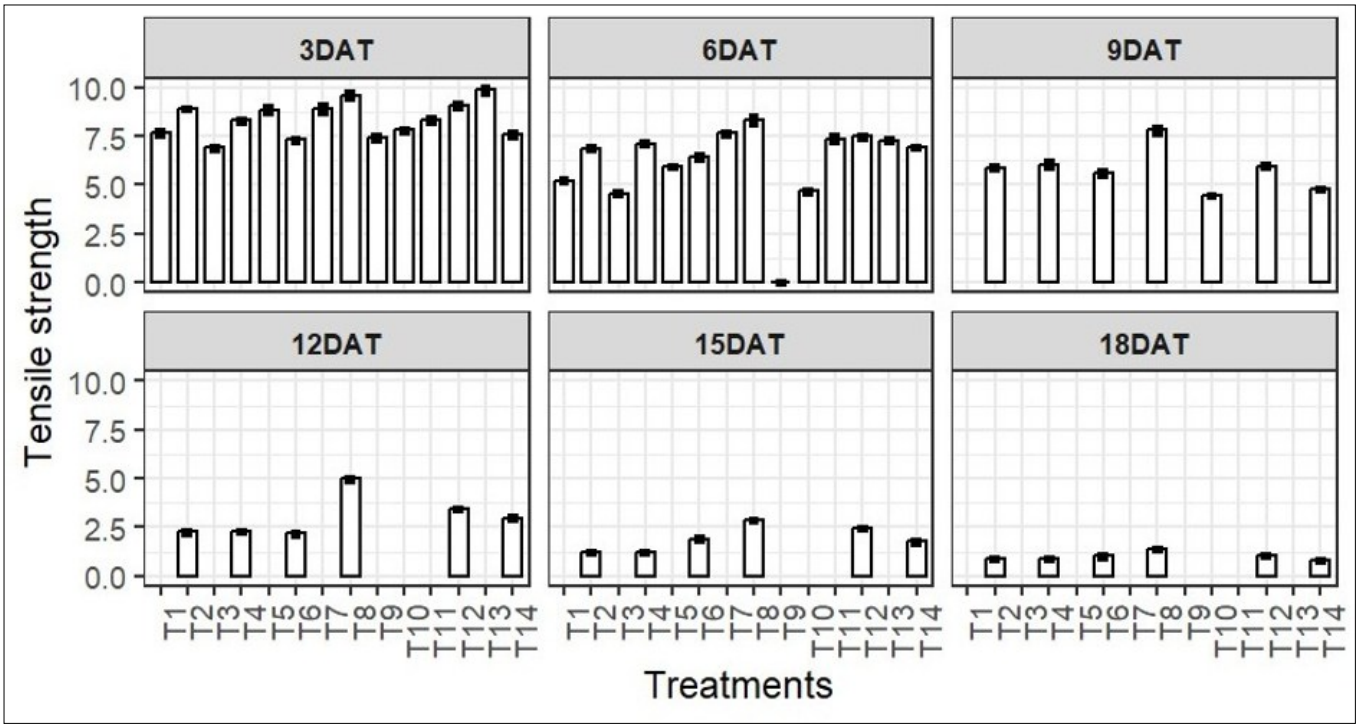


Fig. 3. Effect of post-harvest treatments on tensile strength during storage conditions.

Visual evaluation

Freshness of leaf

Freshness of leaf (score) declined steadily during storage across all treatments. However, significant ($p < 0.05$) variation was observed due to treatment effects. The T_8 maintained the highest freshness score (3.00 at 18 DAP), remaining acceptable even at later stages (Fig. 4). Treatments T_6(2.01 at 18 DAP) and T_4 (1.50 at 18 DAP) were close to the highest, maintaining acceptable freshness for extended periods. The lowest freshness was recorded in T_{13}(1.50), which became unacceptable within a short duration of 6 days (Fig. 5). The complete mean values and statistical groupings for freshness of leaves at each storage interval are provided in Supplementary Table 4. The leaves treated with ascorbic acid + BAP and kept in cold storage at the temperature of 5 ± 2 ℃ (T_8) remained fresh due to reduced moisture loss, delayed senescence and sustained cellular turgidity. In contrast, a rapid decline in freshness was observed in control untreated leaves due to increased transpiration, respiration and loss of cell turgor under ambient conditions**.** Similar trends have been documented in lettuce (*Lactuca sativa* L.) (22).

Leaf colour (Yellowness score)

Leaf yellowness was significantly increased ($p < 0.05$) during storage duration, reflecting chlorophyll degradation and senescence. T_8 recorded the most stable leaf colour profile (lowest yellowness index score) (1.30 at 3 DAP and 4.70 at 18 DAP), indicating delayed yellow colour (Fig. 6A). Treatment T_6(2.00 at 18 DAP) was close to the best, with a yellow colour developing gradually. The highest yellow colour was observed in T_{13}(5.00 at 6 DAP) and T_{14} (5.00 at 18 DAP), indicating a rapid loss of green colour (Fig. 6B). The complete mean values and

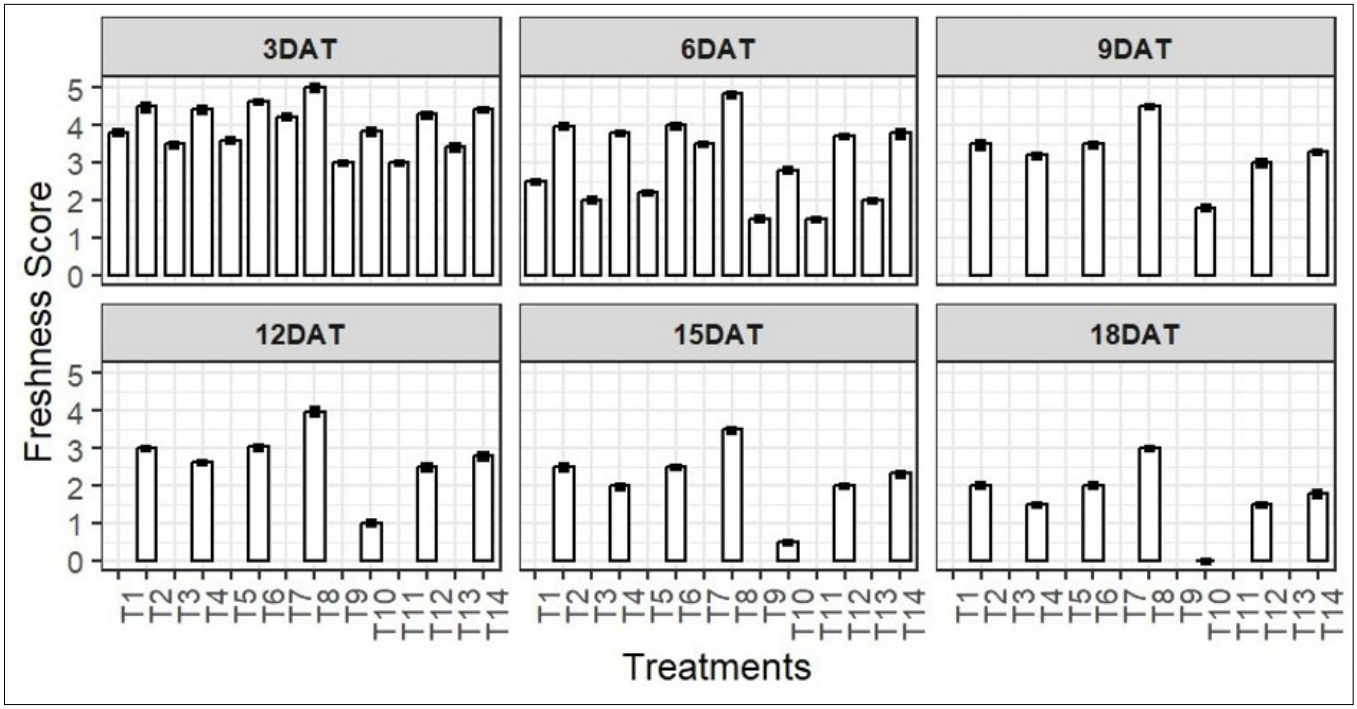


Fig. 4. Effect of post-harvest treatments on leaf freshness during storage conditions.

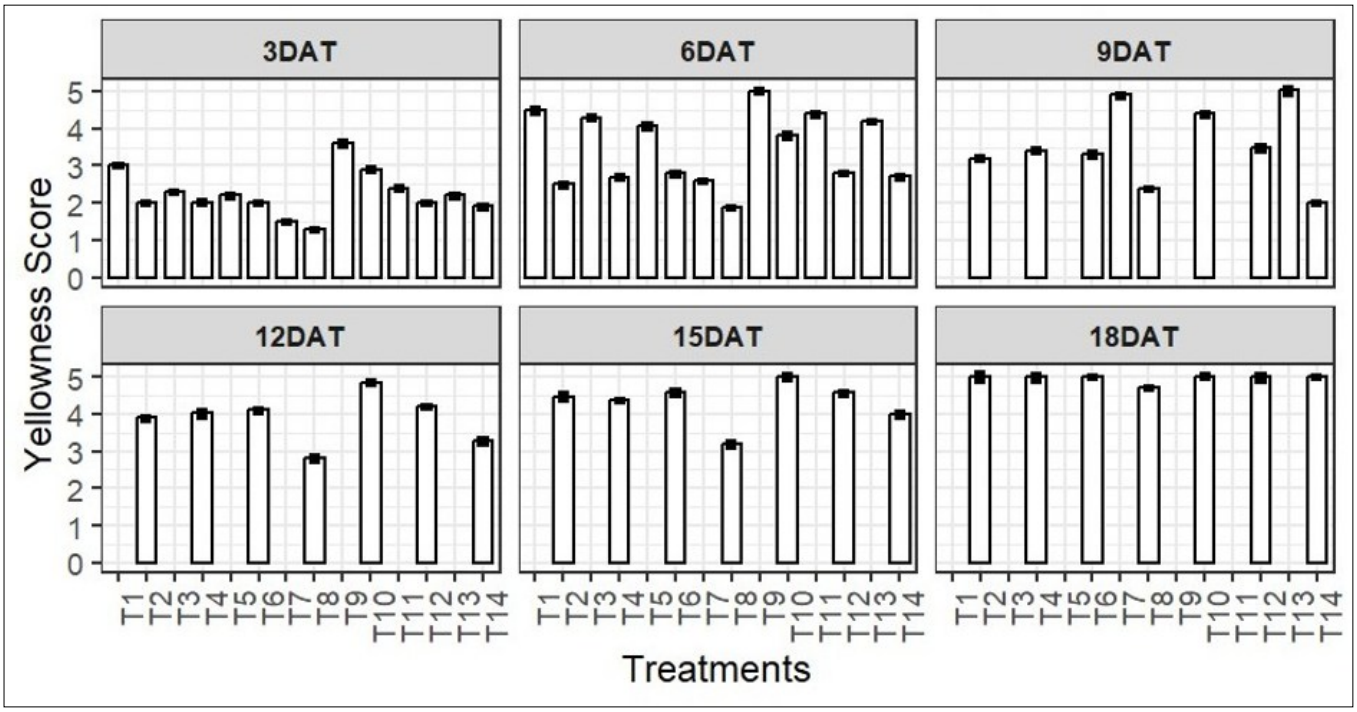


Fig. 5. Effect of post-harvest treatments on leaf colour during storage conditions.

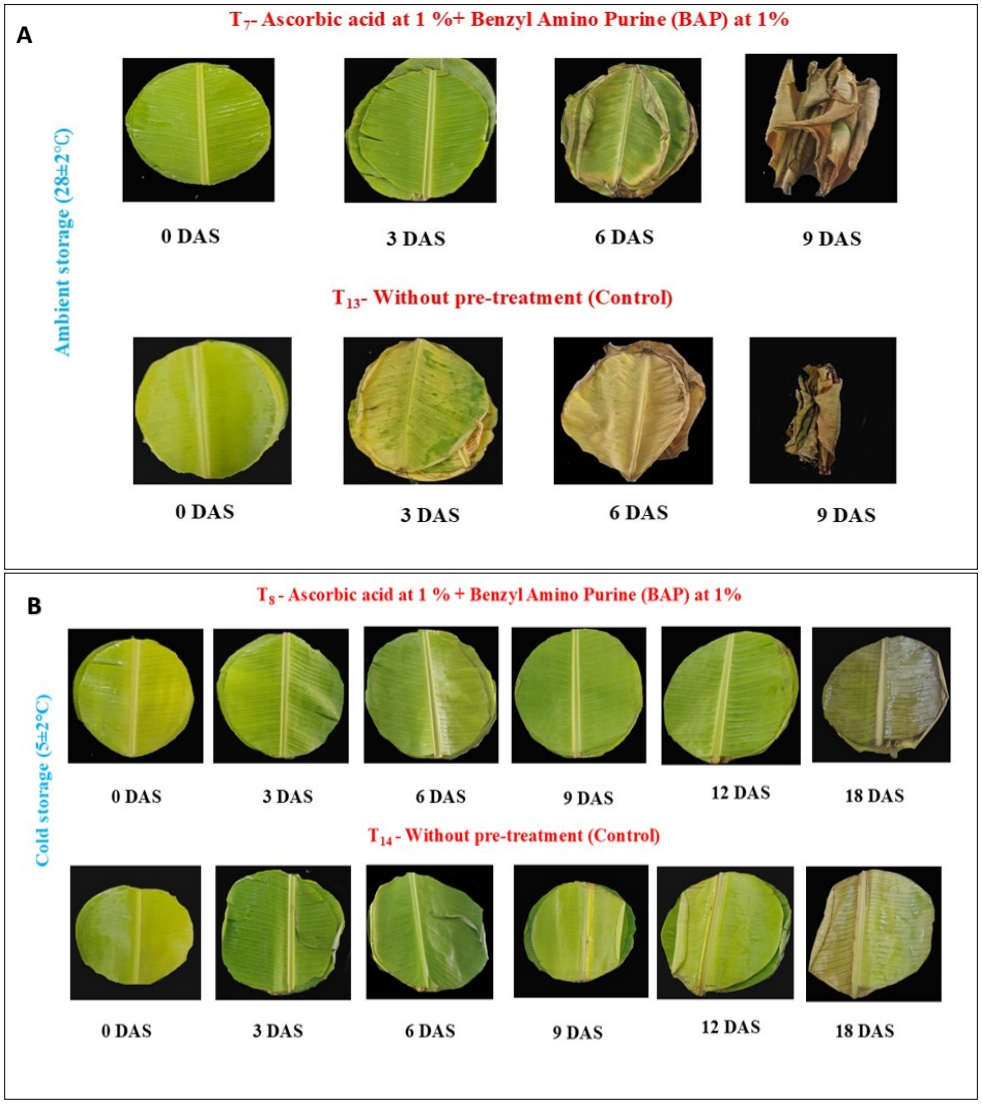


Fig. 6. Representative photographs showing visual quality changes in treated and untreated (control) banana leaves cv. Chakkai Peyan during (A) ambient storage (28 ± 2 °C) and (B) cold storage (5 ± 2 °C). Leaves treated with ascorbic acid (1 %) + BAP (1 %) (T_7 and T_8) retained greener colour, freshness and structural integrity for a longer duration than the untreated controls (T_{13} and T_{14}), demonstrating delayed senescence and extended shelf life. Under ambient storage, treatments T_1, T_3, T_5, T_7, T_9, T_{11} and T_{13} maintained acceptable quality only up to 6 days, after which the leaves became unfit for further evaluation.

statistical groupings for leaf colour (Yellowness Score) at each storage interval are provided in Supplementary Table 5. The delayed yellow colour in T_8 can be attributed to a combination of antioxidant and cytokinin actions that blocked chlorophyll breakdown and senescence. Cold storage further reduced the enzymatic activity responsible for pigment breakdown. In contrast, rapid yellowing in control treatments is due to uncontrolled oxidative reactions and faster chlorophyll degradation under higher temperatures. The same trend was observed in broccoli under cold storage conditions (23, 24).

Shelf life

Significant changes ($p < 0.05$) in shelf life were seen among treatments, emphasising the importance of combination effects. T_8 recorded the longest shelf life (16.50 days) and was significantly superior to T_4 (15.30 days) and T_{12} (15.20 days). The minimum shelf life was observed in T_{13} (4.30 days), followed by other ambient treatments (Fig. 7). The complete mean values and statistical groupings for shelf life at each storage interval are provided in Supplementary Table 6. The extended shelf life in T_8 is the result of synergistic interaction between pre-treatment and cold storage, which collectively reduced PLW %, maintained chlorophyll content, preserved tensile strength, delayed yellowing and sustained freshness. Cold storage lowered respiration and metabolic rates, BAP postponed ageing and ascorbic acid guarded against oxidative damage (2, 8). Overall, the leaf degeneration is considerably slowed down by this dual action. Conversely, accelerated senescence and a shorter shelf life resulted from the absence of both temperature regulation and biochemical protection in control and ambient treatments (22, 25).

Conclusion

The study demonstrated that post-harvest treatments significantly improved the storage life and quality of banana leaves (*Musa* spp. cv. Chakkai Peyan). The combined treatment of 1 % ascorbic acid + 1 % BAP under cold storage (5 ± 2 °C) (T_8) was the most effective, maintaining freshness, chlorophyll content, tensile strength and extending shelf life to 16.5 days. Individual applications of ascorbic acid or BAP under cold storage also performed well, whereas the untreated control under ambient conditions had the shortest shelf life (4.30 days). The superior performance of T_8 was due to the combined effects of antioxidant protection, delayed senescence and reduced metabolic activity under low temperature storage. These findings demonstrate that integrating appropriate post-harvest treatments with cold storage is a practical strategy for extending shelf life and preserving the quality of banana leaves, thereby enhancing their commercial utilisation as a sustainable packaging material.

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Authors' contributions

GS conducted the research, collected and analysed the data and drafted the manuscript. SPR revised and proofread the manuscript. JP and MS revised and formatted the manuscript. GP and SB supervised the study. RV reviewed and approved the final version of the manuscript. All authors contributed equally to this work.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflicts of interests to declare.

Ethical issues: None

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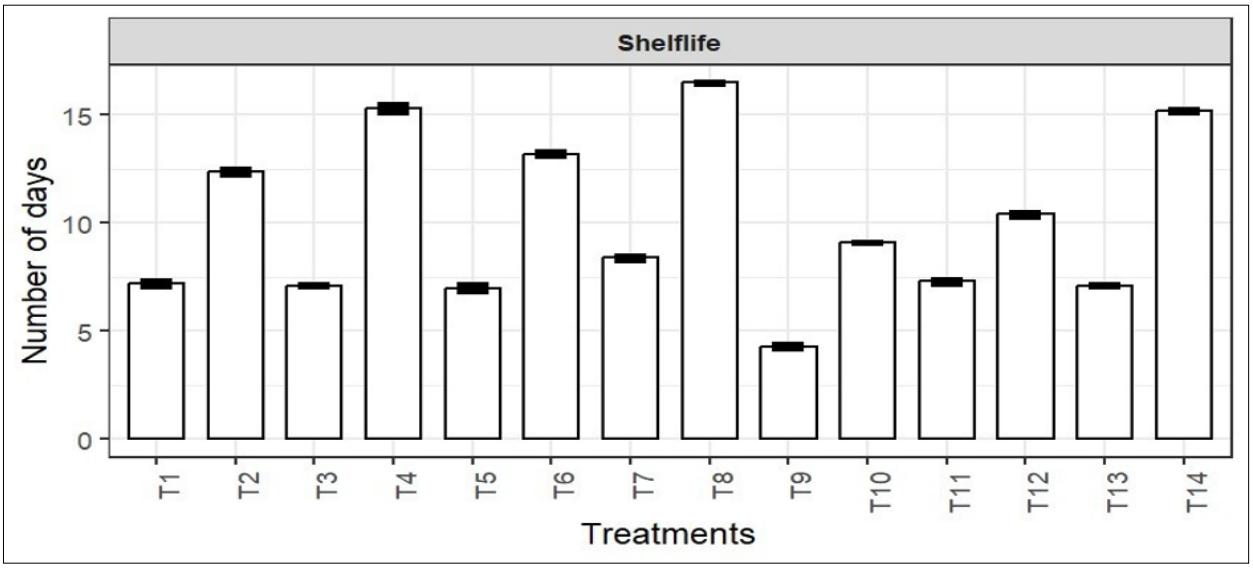


Fig. 7. Effect of post-harvest treatments on shelf life under storage conditions.

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