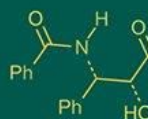


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MC Monpara
Indian Agricultural Research
Institute (ICAR-IARI), New
Delhi, India

Omkar Nagawade
Asar Social Impact Advisors
Pvt Ltd, Ranchi, Jharkhand,
India

Sangeeta Chopra
Indian Agricultural Research
Institute (ICAR-IARI), New
Delhi, India

Indra Mani
Vasanthrao Naik Marathwada
Krishi Vidyapeeth, Parbhani,
Maharashtra, India

Corresponding Author:
MC Monpara
Indian Agricultural Research
Institute (ICAR-IARI), New
Delhi, India

Evaluation of different storage environments of solar refrigerated evaporatively cooled structure on quality of leafy vegetables

MC Monpara, Omkar Nagawade, Sangeeta Chopra and Indra Mani

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Abstract

Considering the increasing shelf life of leafy vegetables, the most important factor to keep the quality is refrigerated storage. The spinach and lettuce under refrigeration and specific relative humidity just after harvest provide decreased breathing by water loss, which affects the addition to weight, total soluble solids, texture, and color. This study aimed to investigate the effect of storage conditions on the shelf life of refrigerated spinach and lettuce. The samples were stored in solar refrigerated evaporatively cooled (SREC) structure, and three storage conditions were taken as ambient, T₄, and T₈. Quality parameters were studied during the storage study. Physiological weight loss in spinach varied from 0 to 22.80%, and for lettuce, it varied from 0 to 20.52% during 14 days of storage. We recorded the maximum bursting strength of the spinach and lettuce at 1.74 N and 1.73 N, respectively. The leafy vegetables can be stored for up to 14 days, and T₄ storage condition is very effective for maintaining the quality and shelf life of lettuce and spinach.

Keywords: SREC, refrigerated storage, lettuce, spinach, evaporative cooling

Introduction

India ranks as the world's second-largest producer of vegetables, following China. In 2023-24, horticulture production was estimated at 354.74 million tonnes, with an expected increase to 362.08 million tonnes in 2024-25 (Anon., 2025) ^[1]. The demand for minimally processed foods has grown due to their convenience, nutritional value, and sensory appeal. These products are sanitized, ready for consumption, and packaged to maintain freshness. However, 30% of food produced for human consumption is lost or wasted due to factors such as inefficient input use, inadequate post-harvest storage, limited processing and insufficient transportation facilities (Rezaei & Liu, 2015) ^[7].

Leafy vegetables undergo continuous biological changes after harvest, including respiration, transpiration, and ethylene production, which can be either beneficial or harmful (Pinto *et al.*, 2000) ^[6]. Carvalho (1999) ^[2] highlights that water loss affects the appearance, flavour, texture, and weight of plant-based foods. To minimize post-harvest losses, various preservation methods are applied, with refrigeration being the most effective in slowing undesirable changes. Factors such as temperature, relative humidity, and atmospheric composition influence the shelf life of leafy vegetables. Cooling methods vary depending on the product, with hydro-cooling using cold chlorinated water through dipping or spraying—being effective for preserving lettuce and spinach.

Spinardi *et al.* (2009) ^[10] studied the post-harvest quality of spinach and lettuce baby leaves stored at 4-10°C. Their findings showed that carotenoids, chlorophyll, and phenols remained stable for up to six days at both temperatures. Manolopoulou *et al.* (2010) ^[4] examined passive modified atmosphere storage of fresh-cut Romaine lettuce at 0 °C and 5 °C using different packaging. They found that respiration remained stable at 0 °C for 10 days but increased at 5 °C. Schvambach *et al.* (2020) ^[8] studied hydroponic crisp lettuce storage under different packaging at 5 °C and 23 °C. Lettuce without packaging had the highest weight loss, reaching 53.6% at 5 °C and 43.7% at 23 °C. This study aimed to evaluate the impact of various storage conditions on the shelf life of lettuce and spinach leaves in a solar refrigerated evaporatively cooled structure.

2. Material and Methods

The research aims to determine the impact of different storage environments on maintaining the freshness and nutritional quality of leafy vegetables. The storage study was conducted in Solar Refrigerated Evaporatively Cooled (SREC) structure at Division of Agricultural Engineering, ICAR-IARI, New Delhi.

2.1 The Solar Refrigerated Evaporatively Cooled (SREC) structure: The SREC structure is a hybrid cold storage system designed for agricultural produce, integrating evaporative and forced cooling. It has a $10 \times 10 \times 10$ ft³ capacity and is powered by a 5-kW rooftop solar panel system connected to an inverter, which supplies energy to a 1.5-ton refrigeration unit (GREE Wall Mount Ductless Mini Split Air Conditioner & Heat Pump, Zhuhai, China) (Chopra *et al.*, 2023) [3].



Fig 1: A view of the SREC structure

The refrigeration system utilizes refrigerant coils to cool water in an internal tank, which is then circulated through PVC pipes, creating a thermal water battery. This system helps maintain a stable internal temperature, particularly during non-solar hours, ensuring efficient temperature regulation for prolonged cold storage of produce.

The control circuit was integrated with the refrigeration system to analyze temperature reduction within the SREC structure. The study evaluated 12 treatment combinations involving two inverter types—off-grid/hybrid (X_1) and on-grid (X_2)—along with two coil thermistor resistance levels ($A_1 = 45$ k Ω , $A_2 = 39.4$ k Ω) and three air thermistor resistance levels ($B_1 = 21$ k Ω , $B_2 = 18.91$ k Ω , $B_3 = 16.94$ k Ω). Each treatment was replicated three times. Treatments were labeled T_1 to T_{12} , with T_1 comprising an off-grid

inverter (X_1), coil resistance A_1 , and air resistance B_1 , while T_4 included an off-grid inverter (X_1), coil resistance A_2 , and air resistance B_1 . Among the evaluated configurations, T_4 and T_8 demonstrated the highest cooling efficiency and were subsequently implemented within the SREC structure for a comprehensive storage study.

2.2 Storage Conditions

In the experiment, the storage study was conducted in two treatments in which the highest cooling efficiency improvement was found. So, the storage behaviour of spinach and lettuce was evaluated by storing them in ambient (AC), T_4 and T_8 storage conditions. During the course of storage, changes in physiological weight loss, total soluble solids, firmness and colour were analysed.



Fig 2: Storage of lettuce and spinach in SREC structure

2.3 Quality Parameters

The PLW of fruit was calculated on the initial weight basis and expressed in percent. Burst strength of Spinach and Lettuce leaf was measured by using a texture analyser (TA-XT plus of Stable Microsystems, Ltd., Surrey, UK) in compression mode with a 5 mm spherical ball probe to penetrate the leaf at a pre-test speed of 2 mm/s, a test speed of 1 mm/s as the probe contacted the leaf and a post-test speed of 10 mm/s (More *et al.*, 2014) [5]. Firmness was measured as the maximum force recorded in a force-time curve obtained during the compression of test material by the probe. The colour of the vegetables in terms of L*, a*, b* values were determined using AMTAST 8MM Digital Precise Color Analyzer. The chromaticity dimension a* depicts redness with +ive, greenness when -ive, and b* measures yellowness when +ive and blueness when -ive. The total soluble solid (TSS) were determined by following the procedure described by Seyoum *et al.* (2011) [9] using hand-held refractometer (Model Misco) with a range of 0 to 32 °Brix and a resolution of 0.2 °Brix and expressed as percent TSS after making the temperature correction at 20 °C. The experiments consisted of 6 treatments and 3 storage condition and laid out in a completely randomized design with five replications.

3. Results & Discussion

3.1 Physiological loss in weight (PLW)

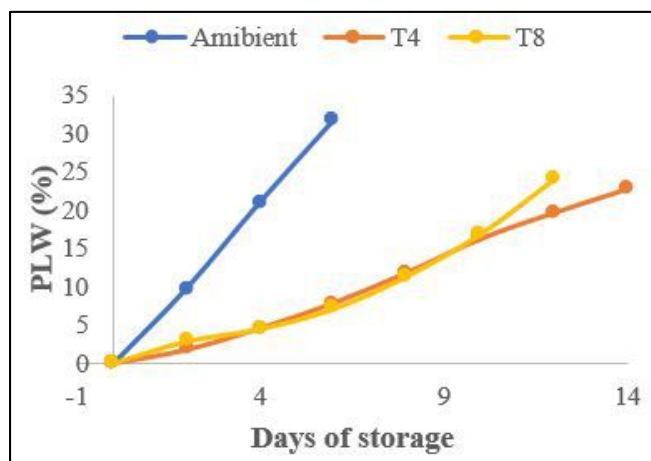


Fig 3: Effect of different storage conditions on PLW of spinach

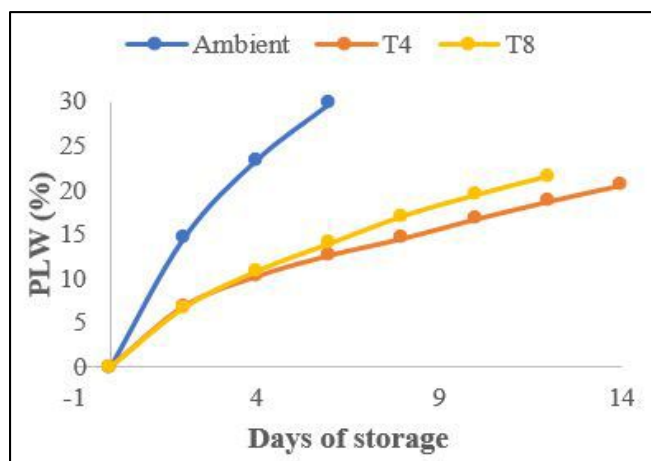


Fig 4: Effect of different storage conditions on PLW of lettuce

The physiological loss of weight (PLW) varied significantly across storage conditions in lettuce and spinach. PLW in spinach increased sharply under ambient conditions (AC), reaching 31.63% in six days, while T₄ had the lowest PLW (22.80% over 14 days) and T₈ recorded 24.08% over 12 days. PLW in lettuce increased rapidly under ambient conditions (AC), reaching 29.74% in six days, while T₄ had the lowest PLW (20.52% over 14 days) and T₈ recorded 21.53% over 12 days. These results indicate that T₄ storage extended spinach and lettuce shelf life by two days compared to T₈, demonstrating superior storage efficiency.

3.2 Total Soluble Solids (TSS)

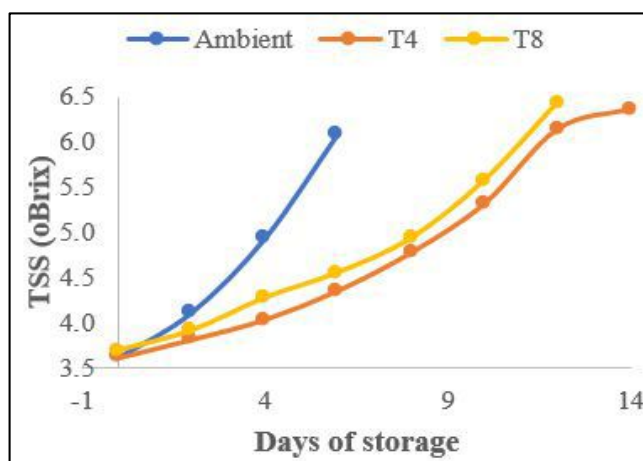


Fig 5: Effect of different storage conditions on TSS of spinach

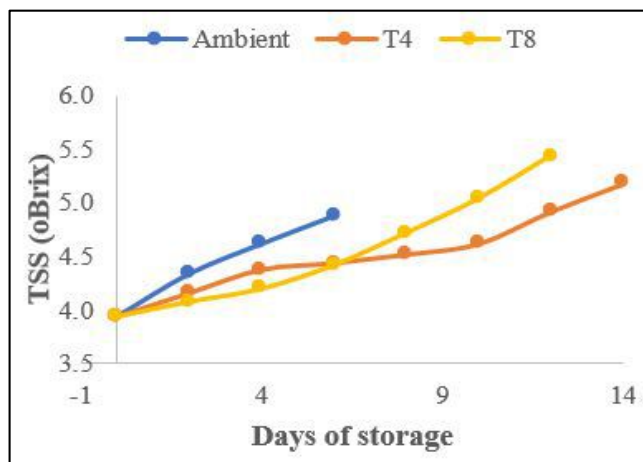


Fig 6: Effect of different storage conditions on TSS of lettuce

A significant difference in TSS was observed across different storage conditions for both lettuce and spinach. The rise in TSS in spinach correlated with PLW, with TSS reaching 6.36°B after 14 days in T₄ and 6.44°B after 12 days in T₈. The TSS in lettuce increased with storage duration, reaching 4.88°B after six days under ambient conditions. TSS in lettuce increased proportionally to PLW, reaching 5.18°B in T₄ after 14 days and 5.44°B in T₈ after 12 days. The slowest increase in TSS was observed in T₄, aligning with PLW trends, indicating that T₄ effectively preserved solids content for a longer duration in both spinach and lettuce.

3.3 Bursting strength and bursting distance of spinach

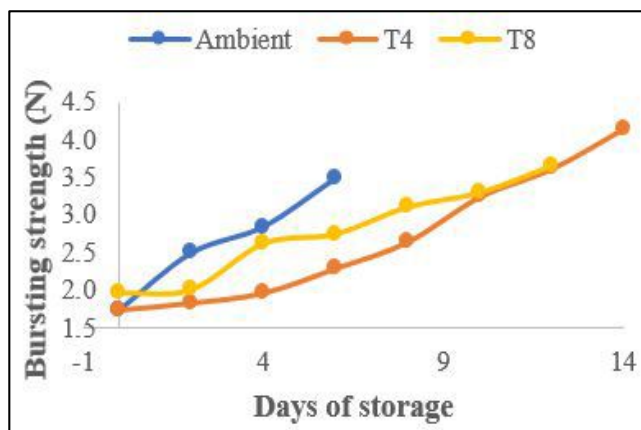


Fig 7: Effect of different storage conditions on bursting strength of spinach

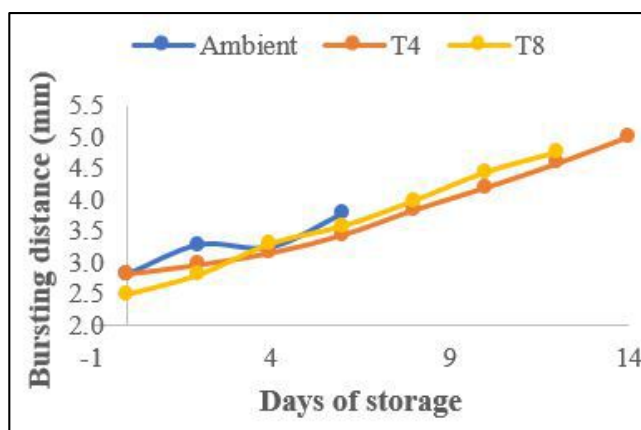


Fig 8: Effect of different storage conditions on bursting distance of spinach

The bursting strength of stored spinach varied significantly. Initially recorded at 1.74 N, it reached 3.49 N, 2.28 N, and 2.75 N on day 6 under ambient, T₄ and T₈ conditions, respectively. The bursting distance of spinach ranging from 2.81 mm to 5.01 mm. The highest increase was observed in ambient conditions, followed by T₈ and T₄. On the final storage day, it reached 5.01 mm in T₄ (day 14) and 4.75 mm in T₈ (day 12). The bursting strength & bursting distance indicates better structural retention in T₄ storage.

3.4 Bursting strength and bursting distance of lettuce

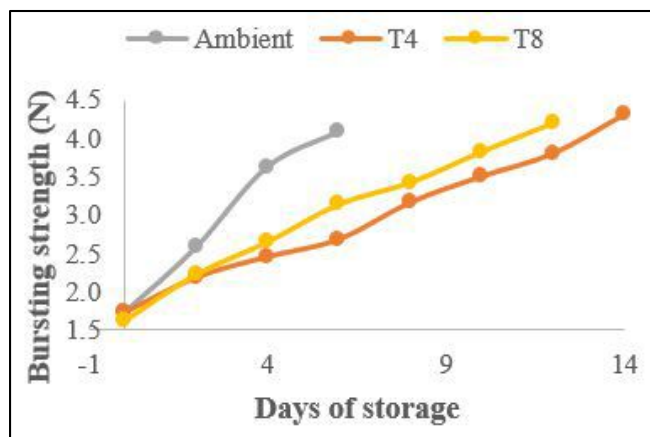


Fig 9: Effect of different storage conditions on bursting strength of lettuce

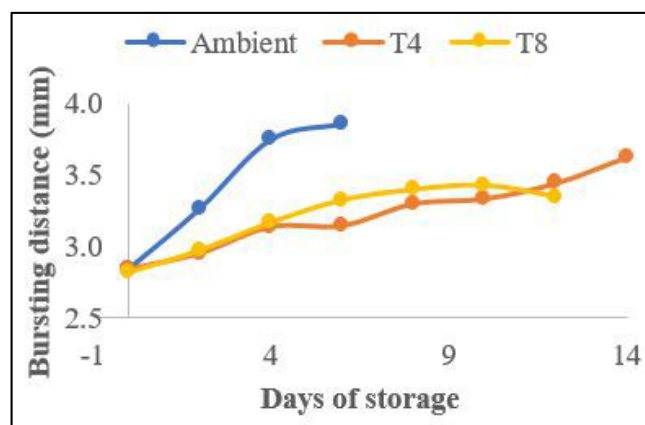


Fig 10: Effect of different storage conditions on bursting distance of lettuce

The bursting strength of stored lettuce varied significantly, initially recorded at 1.73 N. On day 6, it reached 4.09 N (ambient), 2.68 N (T₄), and 3.14 N (T₈). On the final storage day, it was 4.31 N in T₄ (day 14) and 4.20 N in T₈. The bursting distance of lettuce increased from 2.84 mm to 3.63 mm during storage, with the highest rise in ambient conditions, followed by T₄ and T₈. On day 6, it reached 3.86 mm (ambient), 3.14 mm (T₄), and 3.32 mm (T₈). On the final storage day, it was 3.63 mm in T₄ (day 14) and 3.35 mm in T₈ (day 12). The bursting strength and bursting distance of stored lettuce indicating better structural retention in T₄ storage.

3.5 Colour change in spinach

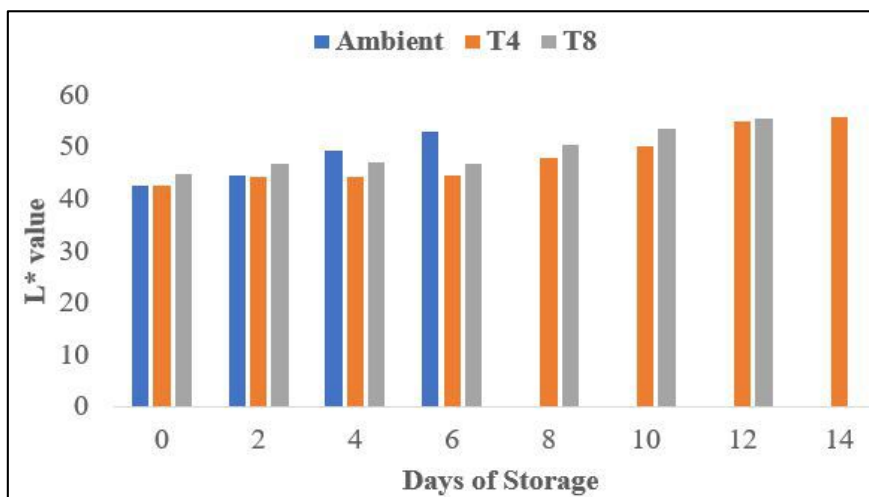


Fig 11: Effect of different storage conditions on L* value of spinach

The L* value increased to 53.15 after six days in ambient conditions. In T₄ storage, it reached 55.87 after 14 days, while in T₈, it increased to 55.65 after 12 days. On day 6,

the L* values were 44.56 in T₄ and 46.79 in T₈, while on day 10, they were 50.29 and 53.63, respectively, indicating a slower increase in T₄ storage.

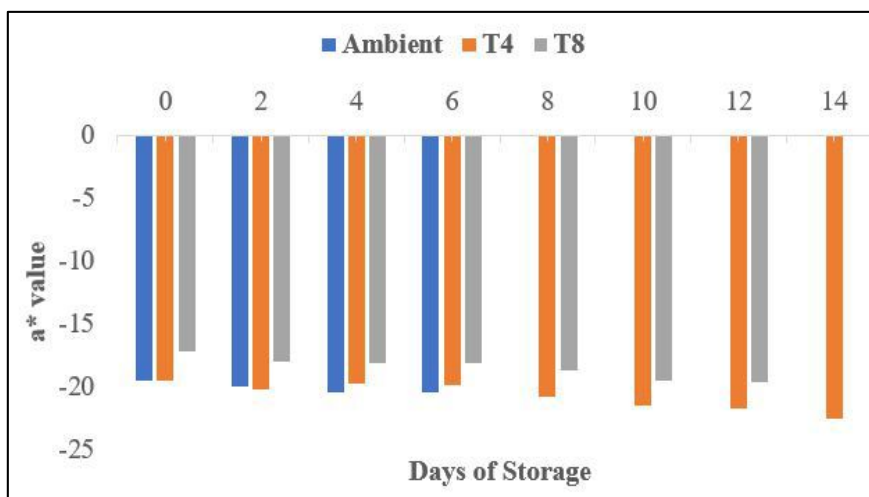


Fig 12: Effect of different storage conditions on a* value of spinach

The a* value increased to -20.38 after six days in ambient conditions. In T₄ storage, it reached -22.55 after 14 days, while in T₈, it increased to -19.60 after 12 days. On day 6, the a* values were -19.89 in T₄ and -18.12 in T₈, while on

day 10, they were -21.52 and -19.47, respectively. Higher a* values in T₄ indicate better retention of greener coloration compared to other treatments.

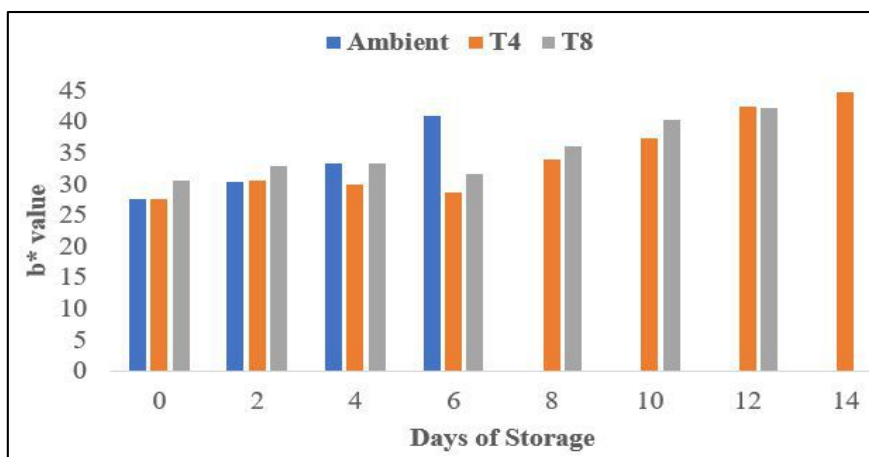


Fig 13: Effect of different storage conditions on b* value of spinach

The b^* value increased to 40.97 after six days in ambient conditions. In T_4 storage, it reached 44.83 after 14 days, while in T_8 , it increased to 42.27 after 12 days. On day 6, the b^* values were 28.78 in T_4 and 31.64 in T_8 , while on day

10, they were 37.49 and 40.28, respectively, indicating a slower increase in T_4 storage.

3.6 Colour change in lettuce

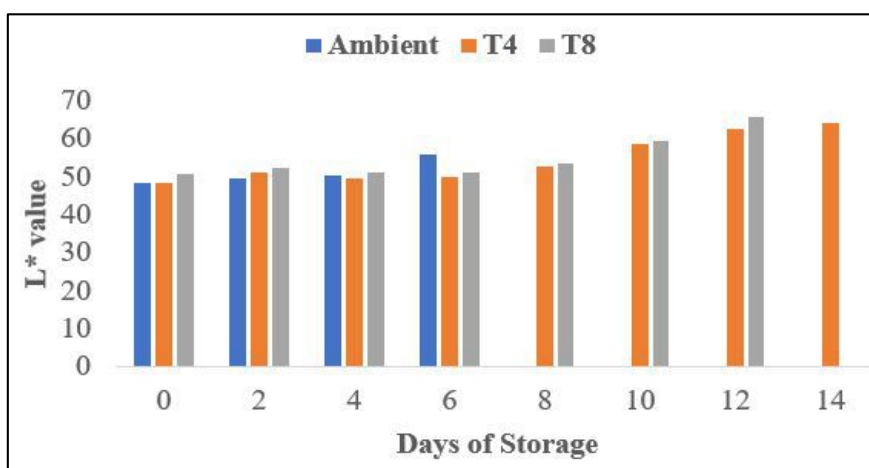


Fig 14: Effect of different storage conditions on L^* value of lettuce

The L^* value increased to 55.78 after six days in ambient conditions. In T_4 storage, it reached 64.14 after 14 days, while in T_8 , it rose to 65.92 after 12 days. On day 6, the L^*

values were 50.07 in T_4 and 51.09 in T_8 , while on day 10, they were 58.47 and 59.43, respectively, indicating a gradual increase in both storage conditions.

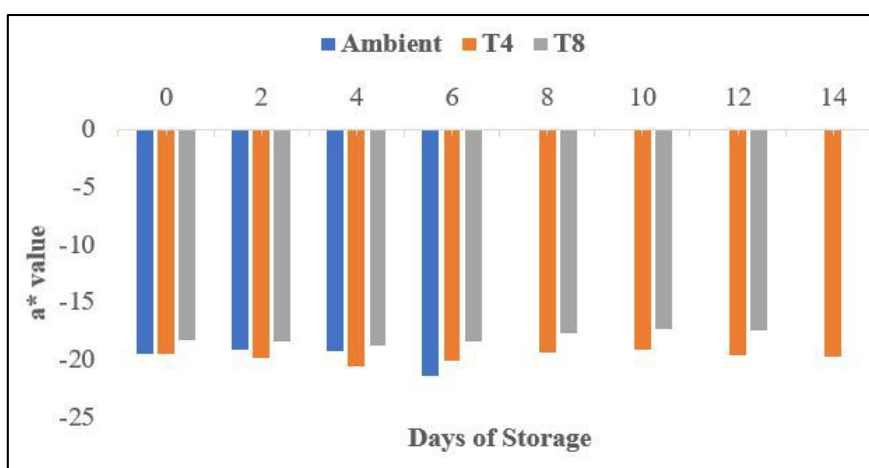


Fig 15: Effect of different storage conditions on a^* value of lettuce

The a^* value increased to -21.31 after six days in ambient conditions. In T_4 storage, it reached -19.68 after 14 days, while in T_8 , it rose to -17.44 after 12 days. On day 6, the a^*

values were -20.09 in T_4 and -18.37 in T_8 , while on day 10, they were -19.14 and -17.33, respectively, indicating better colour retention in T_4 storage.

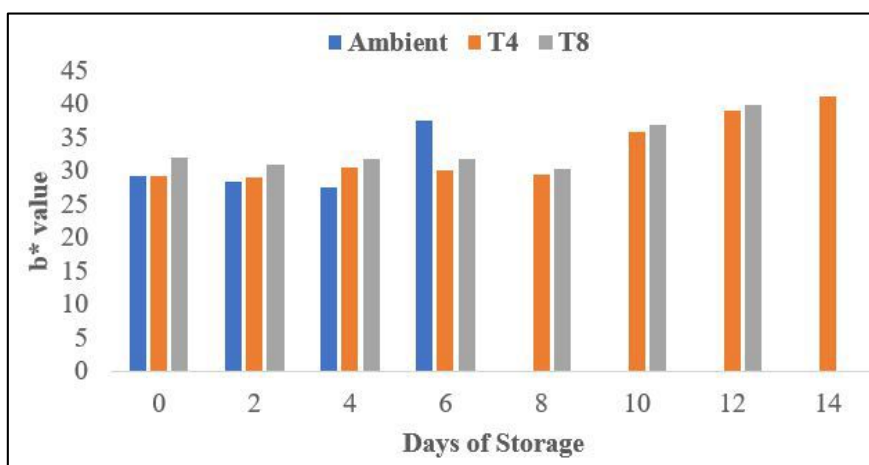


Fig 16: Effect of different storage conditions on b^* value of lettuce

The b^* value increased to 37.68 after six days in ambient conditions. In T_4 storage, it reached 41.20 after 14 days, while in T_8 , it rose to 39.90 after 12 days. On day 6, the b^* values were 30.18 in T_4 and 31.87 in T_8 , while on day 10, they were 35.96 and 36.96, respectively. Higher b^* values indicate increased yellowing of leaves.

Conclusion

The physicochemical properties of the selected horticultural produce were significantly influenced by storage temperature and relative humidity. The SREC structure demonstrated the lowest physiological loss in weight (PLW), while ambient storage resulted in the highest PLW due to increased transpiration and respiration. Total soluble solids (TSS) initially increased due to desiccation and later declined due to sugar consumption for respiration, with the rate of change being faster under ambient conditions. Higher temperatures accelerated respiration, leading to greater shrinkage and structural weakening in spinach and lettuce. Moreover, ambient conditions induced faster colour loss, whereas the SREC structure better preserved colour, with T_4 storage conditions proving superior to T_8 . Overall, T_4 storage conditions in the SREC structure were the most effective in maintaining the quality and shelf life of lettuce and spinach.

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