

Available on <https://www.joarps.org>
Journal of Applied Research in Plant Sciences
(JOARPS)
ISSN: 2708-3004 (Online), 2708-2997 (Print)



Improving Nutritional and Physiological Quality of Green Chilies Using Advanced Atmosphere Packaging Under Different Storage Conditions

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Article Received 01-09-2026, Article Revised 16-09-2026, Article Accepted 18-09-2026

ABSTRACT

This research determined the effectiveness of Modified Atmosphere Packaging (MAP) on the postharvest quality and shelf life of green chilies stored under ambient ($25\pm 2^{\circ}\text{C}$) and cold ($8\pm 1^{\circ}\text{C}$) conditions. The characteristics of physiological and physical, as well as biochemical, quality were evaluated after 12 days of storage. MAP treated chilies minimized weight loss (17.20%), preserved firmness (1.89), slowed color change (1.93), minimized disease incidence (0.89) and decay (0.09%) at ambient temperature considerably compared to the control. Under ambient storage, MAP significantly reduced physiological weight loss, delayed firmness loss, and minimized decay development compared to the control. Under cold storage, the beneficial effects of MAP were further enhanced, with MAP2 demonstrating superior retention of moisture (7.23%), color (1.26), vitamin C ($121.3 \text{ mg } 100 \text{ g}^{-1}$), phenolics (150.7), and antioxidant capacity (50.15). The findings indicated that MAP was more effective under cold storage, suggesting that low temperature and modified atmosphere had a synergistic effect. The research revealed that MAP is a viable and cost-efficient postharvest technology that can be used to extend the shelf life and market quality of green chilies.

KEYWORDS: Modified atmosphere packaging, green chili, postharvest quality, cold storage, shelf life, physiological deterioration.

INTRODUCTION

Green chili (*Capsicum annuum* L.) plays an important role in horticultural production around the globe, based on its culinary role, economic value, and established phytochemical properties (Luca *et al.*, 2021). Chilies are consumed freshly in large quantities in Asia, Africa, and Latin America, where they are used as a primary foodstuff (Ali *et al.*, 2023). Green chilies are widely grown in Pakistan in the Punjab and Sindh areas, and the production volume is growing based on the local market demand and the trade routes (Arin, 2019; Bisht and Singh, 2024). Rapid physiological changes include moisture loss, tissue softening, and chlorophyll degradation (Yang *et al.*, 2025). Green chilies undergo progressive senescence, characterized mainly by dehydration and shrinkage as transpiration and stomatal activity persist (Rajeswari *et al.*, 2024). This physiological loss of moisture not only results in the loss of market value but also affects firmness and visual appeal. At the local market level, processes like postharvest processing are largely manual, and the fruits are exposed to a wide range of ambient temperatures, dust, and mechanical stress (Hamza *et al.*, 2024). The domestic supply chain is mostly

traditional and fragmented, causing delays during transportation and a lack of cold-chain infrastructure, which leads to rapid moisture loss, shriveling, and microbial infections such as bacterial soft rot, anthracnose, Fusarium rot, Botrytis, and mycotoxins (Faqeerzada *et al.*, 2018). The primitive postharvest handling procedures do not control humidity or respiration and cause serious postharvest losses, often exceeding 30-40% under traditional supply chains in local markets (Ahmad *et al.*, 2021). Non-standardized packaging, mishandling, and lack of storage facilities significantly reduce marketable life and stability of the nutrients (Nadeem and Farooq, 2025). This background shows that there is a high demand for scientific preservation strategies such as MAP to ensure quality in the supply chain of Pakistan (Luzzini *et al.*, 2021). Conventional cooling systems may prevent degradation; however, they need infrastructure and energy sources that are usually lacking in low-income agricultural networks (Makule *et al.*, 2022). Therefore, the low-cost packaging methods, including Modified Atmosphere Packaging (MAP), have been recognized as a sustainable option that can actively alter the respiration environment surrounding the

produce without advanced equipment (Wang *et al.*, 2020).

MAP operates by controlling the gaseous composition of the packaging environment, which normally decreases oxygen levels and increases carbon dioxide levels to slow metabolic rates and lower respiration rates (Luzzini *et al.*, 2021). MAP has the potential to improve membrane stability, enzymatic browning, and chlorophyll content, as well as reduce excessive moisture diffusion through the pericarp (Huang *et al.*, 2022). However, the efficacy of MAP differs considerably depending on the permeability of the film and storage conditions.

Some preservation techniques reported by Wang *et al.* (2021) include edible coatings with antimicrobial activity to postpone cucumber spoilage and UV-C treatment to control microbes. Mukhopadhyay *et al.* (2014) used chitosan-lipid composite films in tomatoes and found significant respiratory rate and surface dehydration delays. Comparative studies on MAP in bell peppers conducted, indicated that firmness retention was achieved and fewer incidences of peduncle shriveling were associated with semi-permeable film packaging (Alqahtani *et al.*, 2025). Likewise, research by Mulla *et al.* (2025) illustrated that there was a delay of up to 15th days in color loss among MAP-treated strawberries compared to perforated packaging films. Yahia (2022) found that the effectiveness of MAP was influenced by the ambient humidity and the film transmissibility. Concerning Capsicum in particular, Phillips and Klein (2022) examined the MAP performance in low-temperature conditions in bell pepper; this method is more effective compared to cling film packaging in ambient storage conditions of local fresh markets (Phillips and Klein, 2023). Adewoyin *et al.* (2023) emphasized MAP-induced vitamin C retention in chili varieties under refrigeration, but did not address postharvest physiological responses when cold infrastructure is absent.

This creates a clear research gap: there is limited empirical validation of Modified Atmosphere Packaging (MAP) for green chilies under ambient and cold storage conditions using commercially accessible packaging films that could realistically be adopted by local vendors and supply agents (Faqeerzada *et al.*, 2018; Arin, 2019; Rajeswari *et al.*, 2024). In light of this argument, this research is to generate evidence-based information on the ability of MAP to preserve physiological quality in green chilies during exposure to realistic handling conditions. This study integrates both practical and scientific depth by experimenting with MAP behavior both in ambient and cold conditions with the help of cling film, bridging the gap between laboratory studies and the application in the field. To investigate the efficacy of Modified

Atmosphere Packaging in preserving the postharvest physiological quality of green chilies when stored at ambient and cold temperatures in comparison with traditional cling film packaging.

MATERIALS AND METHODS

Experimental Design and Study Area: The experimental study was done at the Postharvest Research Laboratory, Department of Horticultural Sciences, University of Agriculture Faisalabad, Pakistan, where two independent experiments were developed to determine the effect of Modified Atmosphere Packaging (MAP) on the physiological quality of green chilies (*Capsicum annuum* L). The study utilized a completely randomized design (CRD) factoring in two storage conditions (ambient and cold) and three packaging conditions. All treatments were repeated three times with the aim of providing statistical reliability and reducing random error. The storage time in the experiment was designed to be within the realistic time of market storage of green chilies, which is commonly within 10-15 days in the local trade networks.

Plant Material and Sampling Procedure: Green chilies of standard size and maturity were bought freshly in the peri-urban agricultural belt. Three types of green chilies (Kunri-1, Talhari and Longi) were procured in Sindh (province of Pakistan). Fruits were sorted to remove mechanically damaged or diseased samples. The same-day harvest to postharvest selection was done to preserve physiological homogeneity. Each treatment group was standardized to 500g of fresh produce per sample to compare the surface area-volume ratios and the dynamics of gas exchange in packaging units.

Packaging Treatments: Three distinct packaging treatments were applied. Control (unwrapped): Representing traditional market practice where chilies are exposed to ambient air circulation. Modified Atmosphere Packaging with polyethylene (LDPE) films (MAP2): Performed using low-density polyethylene (LDPE) films of defined gas permeability (approximately 7000 mL m⁻² day⁻¹ atm⁻¹ for O₂, and 14,000 mL m⁻² day⁻¹ atm⁻¹ for CO₂). Modified Atmosphere Packaging with Cling Film MAP1: Used polyvinyl chloride, representing simple wrapping commonly used in retail packaging.

Each packaging unit was heat-sealed to maintain internal atmosphere stability. MAP was created naturally through commodity respiration without external gas flushing, following principles established in similar studies on perishable horticultural crops (Sivertsvik *et al.*, (2002). Headspace gas composition was monitored at 48-hour intervals using a handheld O₂/CO₂ analyzer to confirm the establishment of a modified gaseous equilibrium within the packages.

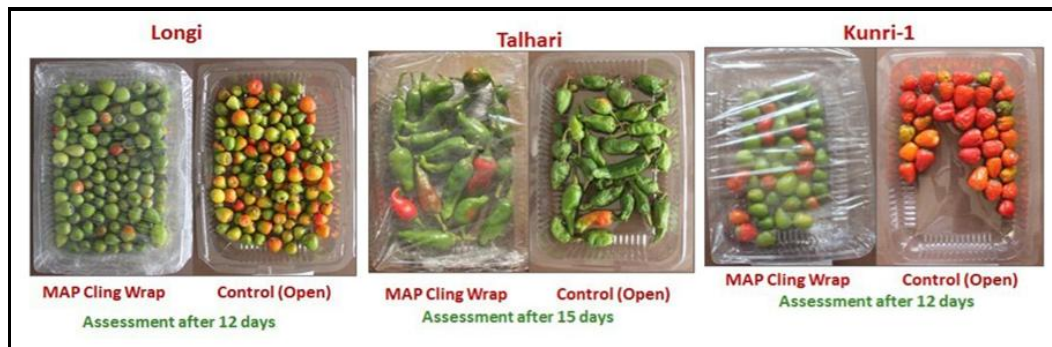


Figure A. Comparative visual appearance of green chilies under different packaging treatments during storage

Storage conditions: Two environmental regimes were applied to simulate real postharvest conditions: Ambient storage: At Room Temperature (RT), $25 \pm 2^\circ\text{C}$ with 65-70% relative humidity (representing local market environments). Cold storage (CS): $8 \pm 1^\circ\text{C}$ with 85-90% relative humidity (representing improved commercial conditions). Storage duration extended up

to 12 days, with sampling performed every 3 days to monitor physiological and visual quality changes.

Physiological Quality Assessment: Weight loss (%) was determined by recording initial and periodic sample weights using a precision balance. Percent weight loss was calculated using the formula, as below.

$$\text{Weight loss percentage} = \frac{(\text{Fresh weight} - \text{dry weight})}{\text{Fresh weight}} \times 100$$

Fruit Firmness (N) was detected using finger feel by applying soft pressure. Firmness readings were taken from three equidistant points per fruit and recorded as below;

1= very firm, 2= slightly soft, 3=moderate, and 4=very soft

Wrinkling index and visual decay were evaluated using a five-point scale (1 = fresh, 4 = severe wrinkling/decay) based on morphological observation protocols (Haq, 2024).

Color Retention was evaluated via visual appearance of the chilies to detect changes in surface hue and brightness during storage, and was scored as 1 = dark green, 2 = Light green, 3 = Greenish red (1-20%), 4 = red-green (20-25% reddish appearance, 5 = complete red (75 %).

Red Color Chilies by weight were measured on a percentage scale using the following formula: Percentage

$$\text{Weight of the red chillies} = \frac{\text{Weight of the red chillies}}{\text{Weight of the total chillies}} \times 100$$

Disease Incidence was recorded as a percentage of visibly infected fruits over the total weight of the chilies. The incidences of the disease were recorded from 0 = No infection to 5 = 100% red

Chemical Characteristics: The chemical properties were considered to establish the impact of Modified Atmosphere Packaging (MAP) on the internal compositional stability of the stored green chilies. The parameters measured were Ascorbic Acid, Total Soluble Solids (TSS), Total Titratable Acidity (TTA), and pH, which together indicate nutritional quality and biochemical changes during storage-related ripening. This flowchart illustrates the step-by-step procedure for quantifying phenolic compounds using the Folin-Ciocalteu (F-C) assay. After vortexing and centrifuging the sample for 3–5 minutes, 100 μL of the resulting supernatant is mixed with 10% F-C reagent and 800 μL of 700 mM sodium carbonate (Na_2CO_3) (Figure B). Following a second vortexing step to ensure thorough mixing, a 200 μL of aliquot of the prepared solution is

transferred to measure spectrophotometric absorbance at 765 nm (Ali *et al.*, 2025).

Additionally, the ascorbic acid content was ascertained by the 2,6-dichlorophenol indophenol (DCPIP) titration method with fresh homogenized chili extract combined with 3 percent of metaphosphoric acid (Dinesh *et al.*, 2015). The endpoint was light pink, which showed the titration was complete, and the results were provided in $\text{mg } 100\text{g}^{-1}$ of fresh weight. A digital refractometer (RX 5000, Atago, Japan measured total soluble solids TSS of green chili juice. According to the protocol as applied in the study by Razali *et al.* (2015) Total Titratable Acidity (TA) was determined by titration of 10 mL of the chili extract with 0.1 N NaOH with the help of phenolphthalein as an indicator. A calibrated digital pH meter was used to measure the pH. Each treatment was prepared at three-day intervals to ensure that the chemical differences were observed with respect to storage period and temperature conditions.

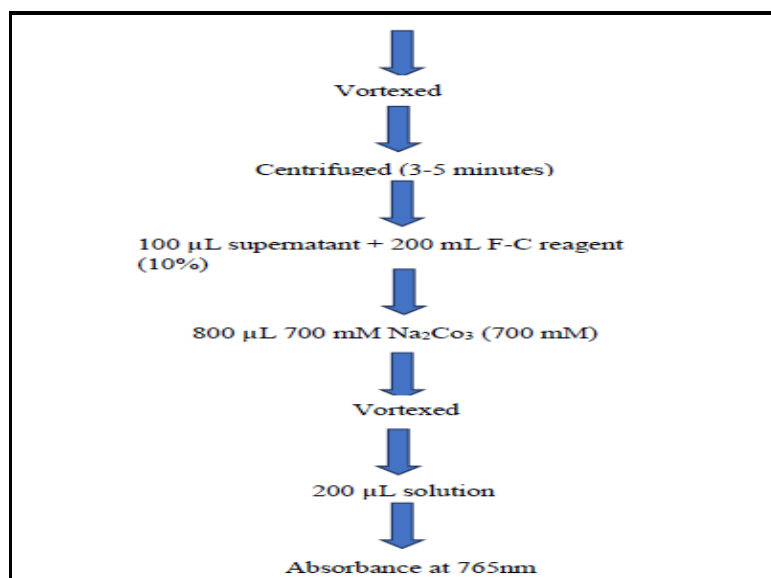


Figure B. Folin-Ciocalteu Method for Total Phenolic Content Analysis

Phytochemicals: The functional and nutraceutical quality of chilies in storage was measured using phytochemical profiling (total phenolic content and antioxidant activity) to monitor chilies. TPC was established using the Folin-Ciocalteu reagent (FC), whereby methanolic extracts of Chili tissue were combined with Folin reagent and sodium carbonate, and then incubated for 30 minutes before reading the absorbance at 765 nm. The values were given in terms

of mg gallic acid equivalents per gram of fresh weight (Sricharoen et al., 2015).

Flow Chart diagram Determining Antioxidant Contents in ‘Chili’ fruit: Antioxidant activity was analyzed through the DPPH radical scavenging assay, in which methanolic extracts were reacted with DPPH solution and absorbance measured at 517 nm to estimate free radical inhibition percentage (Figure C).

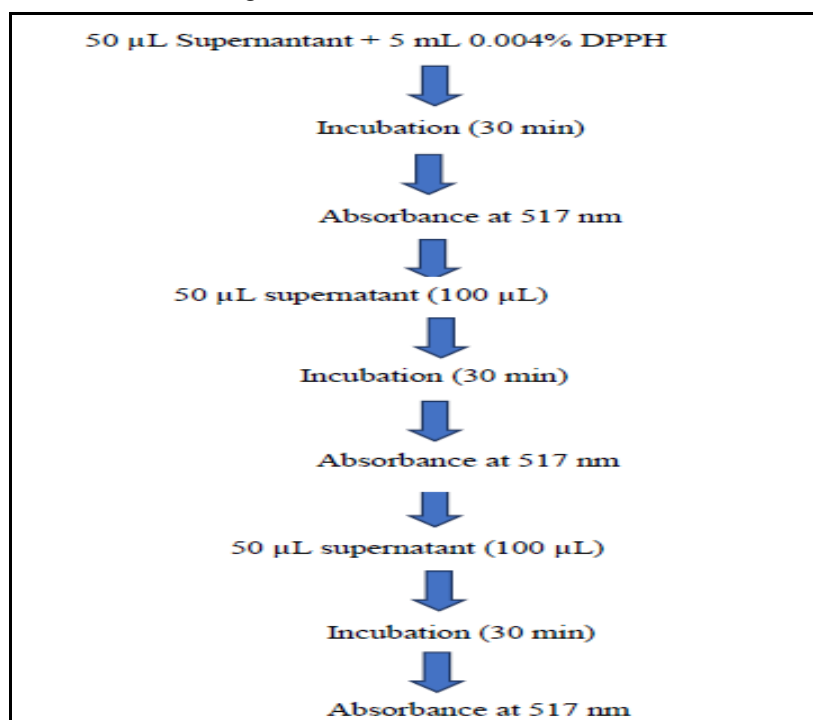


Figure C. Flow chart for estimation of antioxidant of ‘Chili’ fruit.

Statistical analysis: Standard spreadsheet formats were used to organize and tabulate all the recorded data based on the physiological, chemical, and phytochemical observations. Triplicate readings were used to obtain the mean values of each treatment and

observation interval, ensuring the accuracy of the results and minimizing human error. The results were represented in terms of mean ± standard deviation (SD) to show the extent of variation among replicates. Data were analyzed using Fisher’s least significant

difference (LSD) test at $P \leq 0.05$ to calculate means using General Linear Models under a Completely Randomized Design (CRD) (Steel et al., 1997).

RESULTS AND DISCUSSION

Comparative evaluation of the quality attributes of green chili stored at Room (Ambient) Temperature (RT) and Cold Storage (CS) revealed relative differences in the physiological, chemical, and phytochemical aspects. In general, Modified Atmosphere Packaging (MAP) was always more effective than cling film and Control treatments in reducing postharvest degradation. Low temperatures dramatically reduced metabolic activities, resulting in increased freshness, reduced decay rates and preservation of bioactive compounds. On the other hand, storage at room temperature stimulated physiological weight loss and tissue softening, amplified visible shriveling and disease symptoms, and

overall reduced storage life and market acceptability (Lohita and Srijaya, 2024).

Physiological Parameters under Room and Cold Storage Conditions

Weight Loss (%): All treatments showed a gradual increase in weight loss during storage with a sharp difference in the magnitude of the difference between the storage conditions. Control samples kept at ambient storage (RT) would lose weight by 30.5% in 12 days, as compared to 22.4% when kept under the MAP treatment. At day 12, variety “Longi” in control samples lost up to 41.5% of initial weight, while MAP-treated fruits maintained better moisture retention with losses ranging between 8.15% (Talhari) and 32.6% (Longi) depending on variety (Figure 1). The higher weight loss observed in Longi may be attributed to its thinner cuticular layer and higher transpiration rate, which accelerates moisture loss during storage

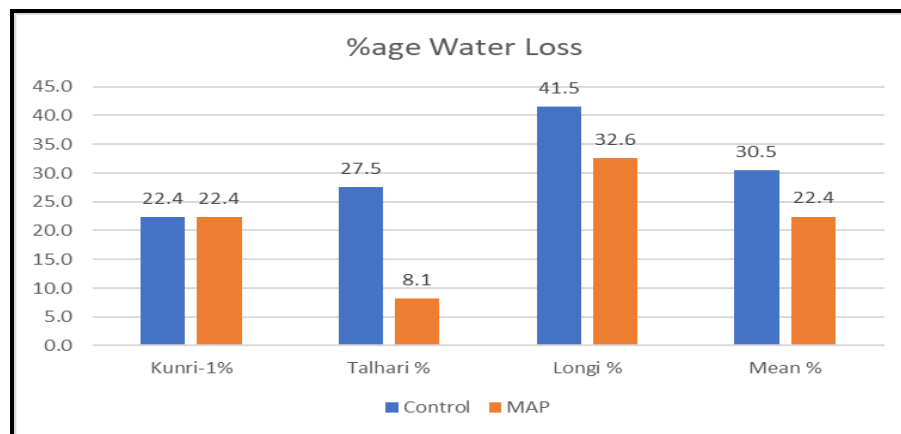


Figure 1. Comparative Weight Loss under RT

Under cold storage conditions, weight loss was substantially lower across all treatments. Control treatment recorded 12% mean loss over 12 days, MAP1 (cling film) showed 9.7%, while MAP2 (XTEND) demonstrated superior performance with

only 7.2% loss (Figure 2). Moreover, maximum water loss was observed in variety “Kunri-1” (22.2 %) at day 12 stored under control conditions, while minimum water loss was observed in variety “Talhari” (2.6%) at day 3 stored under MAP1 packaging (Figure 3).

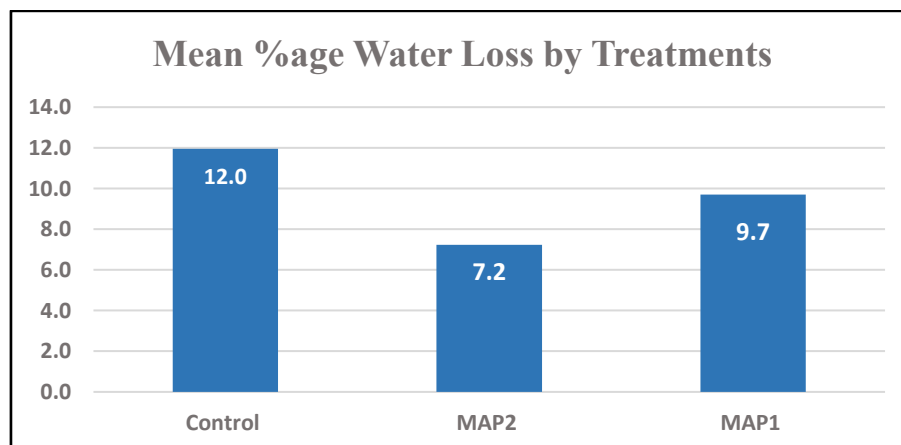


Figure 2. Water Loss Percentage for Control and MAP Treatment

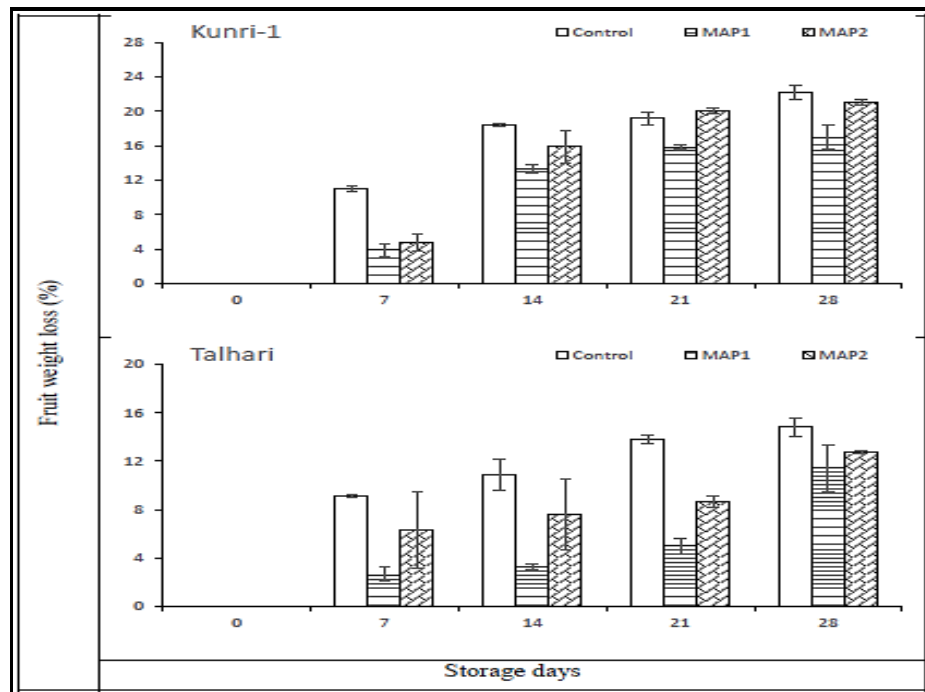


Figure 3. Water Loss Percentage of the Chilli varieties under Control and MAP Treatment

High protection of MAP was linked to low rates of transpiration and respiration in the changed gaseous environment. The semi-permeable LDPE film formed a barrier that reduced the diffusion of water vapors through the surface of the fruit and, at the same time, altered the internal atmosphere via commodity respiration. High CO₂ and low O₂ levels in MAP packages successfully inhibited metabolism, thus decreasing respiration-induced moisture loss as well as transportational water loss by the stomata and cuticular routes. These findings correlate with the results of the study conducted by Lufu et al. (2019), who stated that MAP reduces vapor-pressure deficit and postpones dehydration of fresh produce.

Fruit Firmness (N): The quality of texture, which was measured by the firmness scoring, decreased gradually in ambient storage but was much better maintained

under MAP conditions. Stored chilli pods in MAP + CS had better firmness values, but the fastest textural breakdown was observed in chilli pods kept in RT + Control. Control samples showed a faster softening process with a mean firmness score of 1.99, showing considerable textural deterioration, and MAP treatment showed better firmness with 1.89 mean score after 12 days of storage at RT (Table 1). Thereby, the gradual reduction of firmness was more evident in control samples at the end of the 12th day when fruits became significantly soft and lacked structure, whereas MAP-treated fruits had significant preservation of texture and finger pressure resistance. The preserved firmness in MAP-stored chilies is explained by the lower levels of accumulation of ethylene and inhibition of cell-wall-degradation enzymes, which is enhanced by high temperatures (Opoku, 2011).

Table 1. Fruit Firmness Score across Treatments at RT

Treatment	Varieties			Mean
	Kunri-1	Talhari	Longi	
Control	1.04678	2.0600	1.8400	1.9822
MAP	2.2733	1.7267	1.6667	1.8889

Under cold storage condition, data regarding effect of different packaging material on varieties of chilies showed that control treatment had less mean firmness (1.25) than MAP2 (1.47) and MAP1 (1.33). Furthermore, varieties mean values showed that variety “Talhari” had less mean firmness in fruit (0.97) than

“Kunri-1” (1.65) (Figure 4). The improved firmness retention in Kunri-1 is associated with stronger cell wall structure and lower enzymatic softening activity, which delays textural degradation during postharvest storage (Hasan et al., 2024).

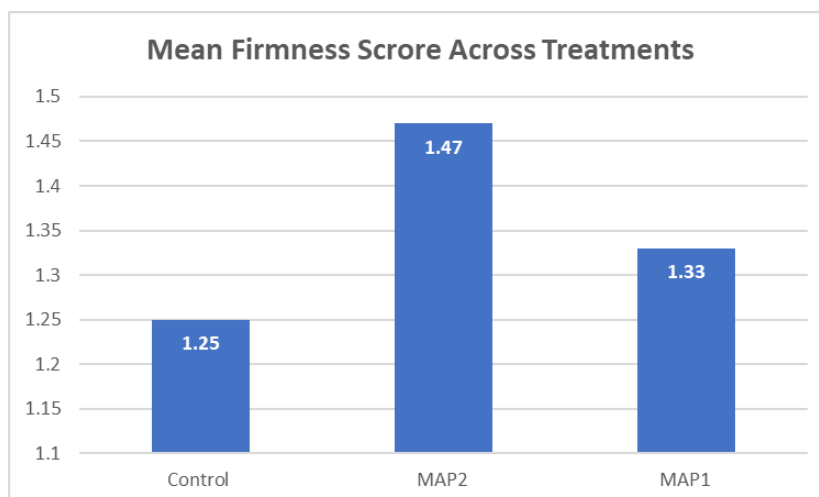


Figure 4. Fruit Firmness Score across Treatments at CS

The mechanistic explanation of the retention of firmness of MAP-treated chilies is the lower activity of the cell wall-degrading enzymes in modified atmospheric conditions. The high concentrations of CO₂ in MAP packages suppress the action of polygalacturonase PG and pectin methyl esterase (PME) enzymes, which play the major role in the solubilization of pectin and breakdown of the middle lamella during fruit ripening and senescence. Also, the low respiration rate at MAP conditions reduces the amount of catabolism that leads to loss of turgor and dissolution of cell structure.

Fruit Color: Color retention is a parameter of quality that has a direct effect on consumer acceptance and

market value. Under ambient conditions (RT), there were significant differences in the preservation of colors with MAP treatments over control samples. The control fruits showed faster color change with an average of 2.31, which reflects that there was a great deal of change to light green and reddish in color change. Conversely, the fruits that were treated with MAP had preserved a better green color with a mean of 1.93 after 12 days (Table 2). By day 12, severe discoloration was visually evident in control samples of “Kunri-1”, with scores reaching 3.5, while MAP-treated fruits retained a substantially darker green color with minimal advancement toward red pigmentation (Table 2).

Table 2: Fruit Color Score Across Treatments at Ambient Temperature

Treatment	Varieties			Mean
	Kunri-1	Talhari	Longi	
Control	2.4533	2.8000	2.1067	2.2311
MAP	1.4267	2.4533	1.9333	1.9378

Under cold storage (CS) conditions, data regarding the effect of different packaging materials on varieties of chilies showed that the control treatment had a higher mean fruit color score (1.56) followed by MAP1-treated chilies (1.38) and MAP2 (1.26) (Figure 5). Data

regarding storage days showed that the fruit color increased day by day in all varieties. The mean value showed that “Kunri-1” had a lower mean color score (2.6) than “Talhari” (1.51) (Table 3).

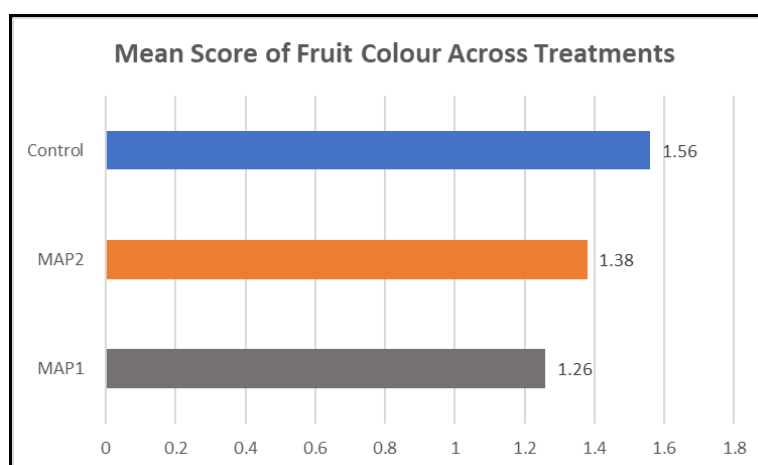


Figure 5. Fruit Color Scores for Different Treatments at CS

The chlorophyll retention under MAP suggests a slower oxidative conversion of chlorophyll a to pheophytin and suppressed synthesis of carotenoid and capsanthin pigments, attributed to reduced O₂ concentration and increased CO₂ buffering. Under normal atmospheric conditions, the high oxygen availability accelerates chlorophyll breakdown through oxidative enzymatic pathways, simultaneously unmasking pre-existing yellow xanthophylls and promoting synthesis of red pigments characteristic of chili ripening. The altered environment provided by MAP, which had less O₂ and higher CO₂ concentrations, effectively prevents these oxidative reactions and slows down the enzyme machinery involved in pigment conversion, maintaining the commercially desirable green hue during the storage period. These findings agree with Zhang et al. (2021),

who observed that color stability was a direct measure of slowed senescence in MAP-stored vegetables.

Disease Incidence (Score 1-5): There was a progressive rise in incidence of diseases with room-temperature storage, and the packaging treatments differed clearly. The mean disease incidence score of control fruits was 1.29 as compared to MAP-treated chilies, which recorded a lower score of 0.89 after 12 days, meaning that the control fruits were more resistant to disease development. During the storage time, disease symptoms were not present at day 0 but increased with time, especially among the control samples. The peak of the disease incidence according to the control fruits was reached by “Longi” (1.76) and the lowest according to the MAP-treated fruits was reached by “Talhari” (0.72), indicating slower infection progression in the modified atmospheres.

Table 3. Mean Disease Incidence Score Across Treatments at CS

Treatment	Varieties			Mean
	Kunri-1	Talhari	Longi	
Control	1.0067	0.7200	1.7600	1.2978
MAP	1.1267	0.7407	1.2067	0.8891

The cold storage significantly decreased the disease incidence in all treatments. The mean score in control fruits was 0.93, MAP1 reduced disease occurrence to 0.59 and MAP2 reduced the disease occurrence to 0.34 (Figure 6). The disease development was also slowly rising with the length of storage; but the treatment of fruits with MAP and in particular MAP2 posted lower disease scores than the control sample during the entire duration of storage.

The lower rate of disease in the MAP-treated chilies in both storage conditions demonstrates the effect of atmospheric alteration in restricting pathogen growth.

Reduced oxygen levels and maintained humidity in MAP probably inhibited the development of microorganisms and delayed symptoms. The further decrease in cold storage implies a synergistic effect, in which low temperature further inhibits pathogen metabolism. Conversely, increased disease scores of control fruits may be explained by the free exchange of gases and moisture, which promotes the spread of infection. Generally, the results validate that MAP, especially in conjunction with cold storage, is a useful method of reducing disease occurrences and preserving postharvest quality of green chilies.

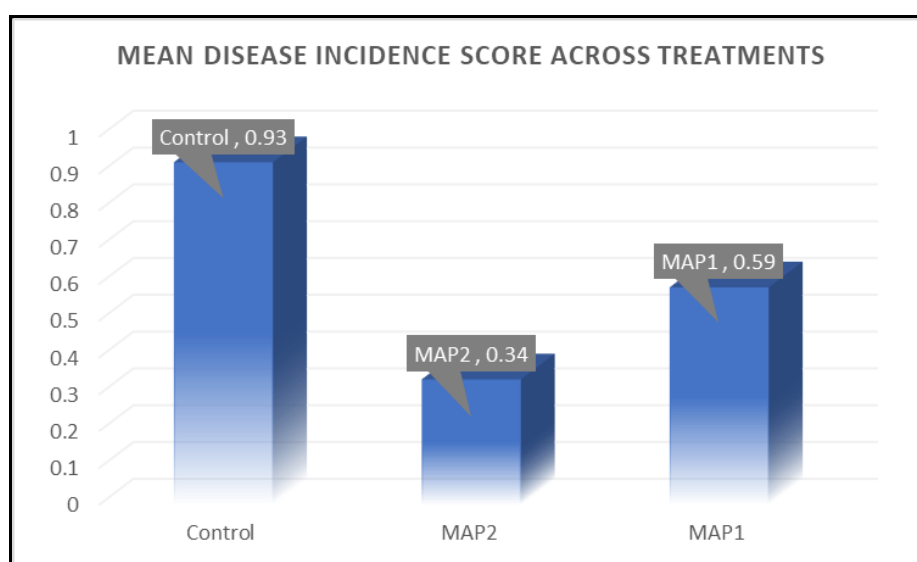


Figure 6: Mean of Disease Incidence Score Across Treatments at CS

Decay Percentage: There was a progressive increase in fruit decay with storing in room temperature and a

significant difference in the packaging treatment. Control fruits had a larger mean percent of decay

(0.29%) than the MAP-treated samples, where the decay level was significantly lower (0.09) at day 12 (Table 4). Even though the varietal difference was not statistically significant, the general tendency was that unpackaged fruits were more vulnerable to microbial degradation. Minimal growth of decay was observed in the initial period of storage (day 0 to day 6) in both treatments, but as the storage duration increased, the

control fruits showed signs of decay, with a maximum of 0.40% in the Longi variety, with no significant effect recorded in the MAP fruits (Table 3). The continuously reduced values of decay in varieties under MAP suggest that altered atmosphere conditions effectively inhibited the decay process of ambient storage through the formation of an unfavorable microbial growth environment

Table 4. Mean percentage decays across treatments and varieties

Treatment	Varieties			Mean
	Kunri-1	Talhari	Longi	
Control %	0.2000	0.2667	0.4000	0.2889
MAP %	0.1333	0.0	0.1333	0.0889

When the storage was under cold conditions, the incidence of decay was further decreased under all the treatments. The mean decay of control fruits was 0.20% and that of MAP1 was 0.03% and MAP 2 had none (0.00%). During the storage, the control samples began to decay more than MAP-treated fruits, especially MAP2, which continued to have almost no decay. The findings indicate that cold storage and modified atmosphere packaging are effective in decay management during the post harvesting process

The lower decay percentages observed in MAP-treated chilies under both room temperature and cold storage conditions demonstrate the effectiveness of modified atmosphere packaging in suppressing postharvest deterioration. Reduced oxygen availability within MAP likely slowed respiratory activity and limited fungal lesions, while stabilized humidity prevented surface moisture accumulation that typically accelerates decay. The markedly lower decay levels under cold storage further indicate a synergistic effect between low temperature and atmospheric modification. In contrast, higher decay in control fruits can be attributed to unrestricted gas exchange and

moisture condensation, which create favorable conditions for microbial proliferation. This trend corroborates prior reports by Li *et al.* (2025), who observed that controlled atmospheres significantly restrict decay development in fresh horticultural produce.

Wrinkling and Shriveling (%): Wrinkling increased significantly during room-temperature storage, with clear differences between treatments. Control fruits recorded a higher mean wrinkling score (1.58) compared with MAP-treated chilies (0.20). Wrinkling progressed steadily over storage days in all samples; however, MAP markedly reduced surface shriveling, indicating improved moisture retention and delayed dehydration compared with unpackaged fruits. Across varieties, wrinkling development was more prominent in Kunri-1 under control conditions, whereas Talhari and Longi showed minimal wrinkling when stored under MAP. Differences in wrinkling response among varieties may be due to variation in epidermal elasticity and water-holding capacity, which directly influence surface shriveling during moisture stress (Hasan *et al.*, 2024)..

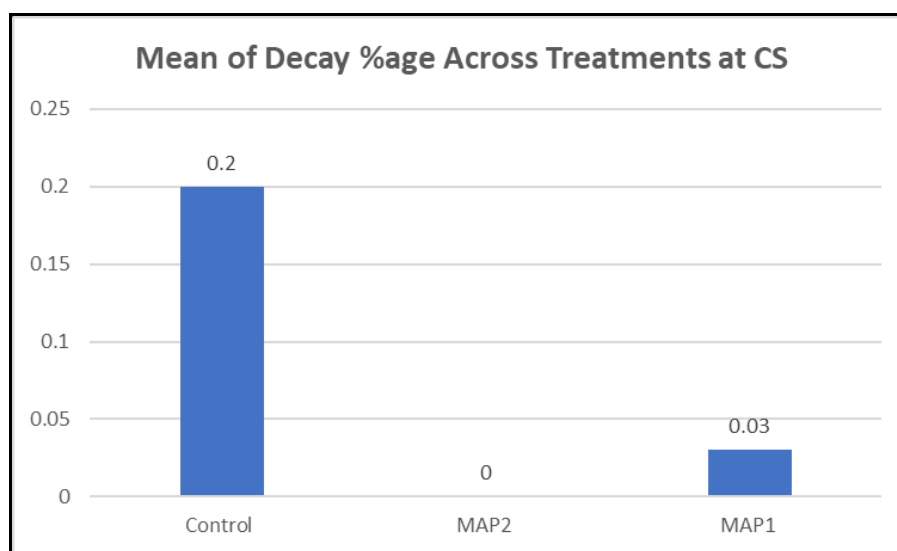


Figure 7. Mean Decay % Across Treatments at Cold Storage (CS)

Table 5. Mean Percentage of Wrinkling Across Treatments at Ambient Temperature (RT)

Treatment	Varieties			Mean
	Kunri-1	Talhari	Longi	
Control	1.5667	1.5667	1.6133	1.5822
MAP	0.6040	0.0	0.0	0.2013

Cold storage reduced wrinkling across all treatments, though control fruits still showed the highest mean wrinkling (0.71%). MAP treatments further minimized wrinkling, with MAP2 (0.39%) and MAP1 (0.28%)

performing better than control. Overall, MAP enhanced the protective effect of cold storage by limiting moisture loss and surface shrinkage.

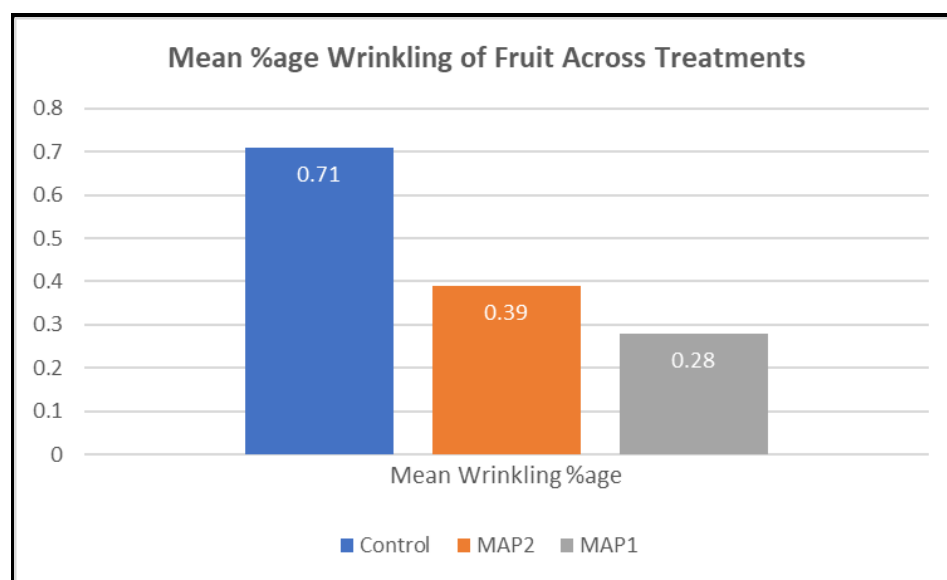


Figure 8. Mean Percentage of Wrinkling in Fruits Across Treatments at CS

The fact that lower wrinkling scores were recorded in MAP-treated chillies at both storage conditions means that atmospheric modification is effective in reducing transpiration and moisture loss. Limited gaseous exchange in MAP also contributes to preserving tissue turgidity and retards dehydration, and cold storage also inhibits physiological activity. Conversely, increased wrinkling of control fruits indicates a high rate of water loss under unlimited conditions. These findings affirm that MAP, especially using cold storage, is a valid method of maintaining the external quality and marketability of green chili

Red Chillies Percentage: There was a progressive increase in the percentage of fruits displaying red coloration during the course of storage, which is a measure of ripening progress. Control samples showed faster ripening under ambient conditions, where 23.80% of the fruits turned red, in contrast to 14.73% of MAP-treated fruits after 12 days (Table 6). This large difference in ripening rate indicates the ability of MAP to delay senescence processes and increase the length of the green marketable season of chillies.

Table 6. Mean Percentage Redness Across Treatments at RT

Treatment	Varieties			Mean
	Kunri-1	Talhari	Longi	
Control	19.979	10.745	19.933	23.807
MAP	31.508	14.777	18.684	14.736

The development of red colour in cold storage was highly different depending on treatments. Control fruits recorded the maximum mean percentage of red chillies (13.59%), which suggests faster ripening. MAP treatments slowed colour change effectively with

MAP1 showing 10.32% and MAP2 showing 7.08% red fruits (Figure 9). In general, MAP decreased pigment formation and preserved greener fruit appearance in cold storage.

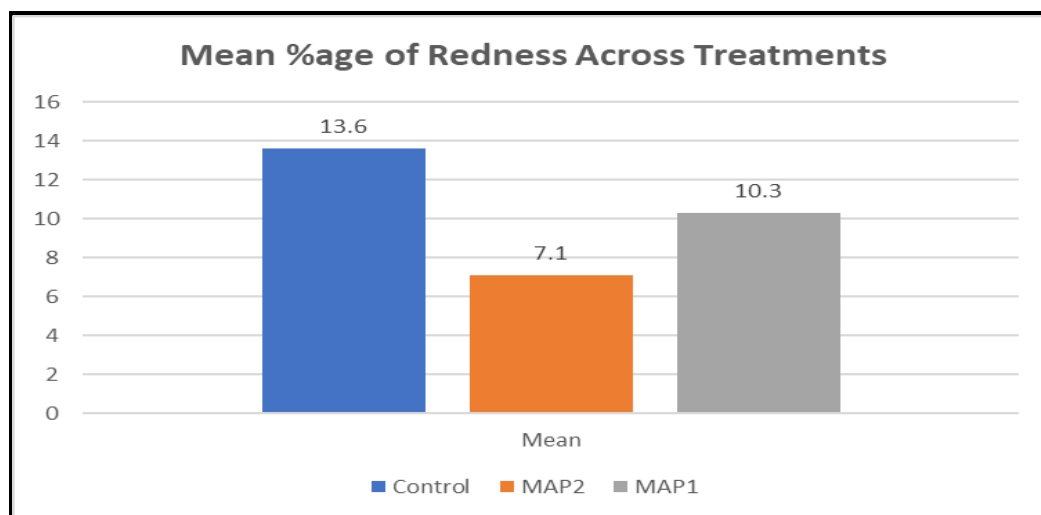


Figure 9. Mean of Percentage Redness Across Treatments at CS

The retarded color change of MAP is physiologically associated with a decrease in ethylene activity and inhibition of enzyme activity during ripening. Green chilies are non-climacteric fruits that do not show significant ripening effects mediated by ethylene, but trace ethylene synthesis and oxygen supply still play a role in pigment biosynthesis pathways. The changed atmosphere successfully suppresses these processes, thus increasing the time in which fruits are kept in a commercially desirable green color.

Chemical Characteristics under Both Storage Conditions

Ascorbic Acid (Vitamin C): The storage time and the interaction of vitamin C with the packaging played an

important role in determining its content at room temperature. MAP-treated chilies had higher average vitamin C ($74.9 \text{ mg } 100 \text{ g}^{-1}$) than control ($73.22 \text{ mg } 100 \text{ g}^{-1}$). Longi was found to have significantly more vitamin C ($114.5 \text{ mg } 100 \text{ g}^{-1}$) compared to Kunri-1 ($49.20 \text{ mg } 100 \text{ g}^{-1}$) (Table 7). The higher ascorbic acid content in Longi may be attributed to genotypic differences in antioxidant enzyme activity and reduced oxidative degradation (Akhter *et al.*, 2024). Vitamin C decreased gradually with storage duration in all treatments which suggested degradation due to ripening and senescence.

Table 7: Mean of Vitamin-C $\text{mg } 100 \text{ g}^{-1}$ in Chilli Across Storage Treatments at RT

Treatment	Varieties			Mean
	Kunri-1	Talhari	Longi	
Control	74.754	70.164	74.754	73.224
MAP	76.066	72.787	76.06	74.973

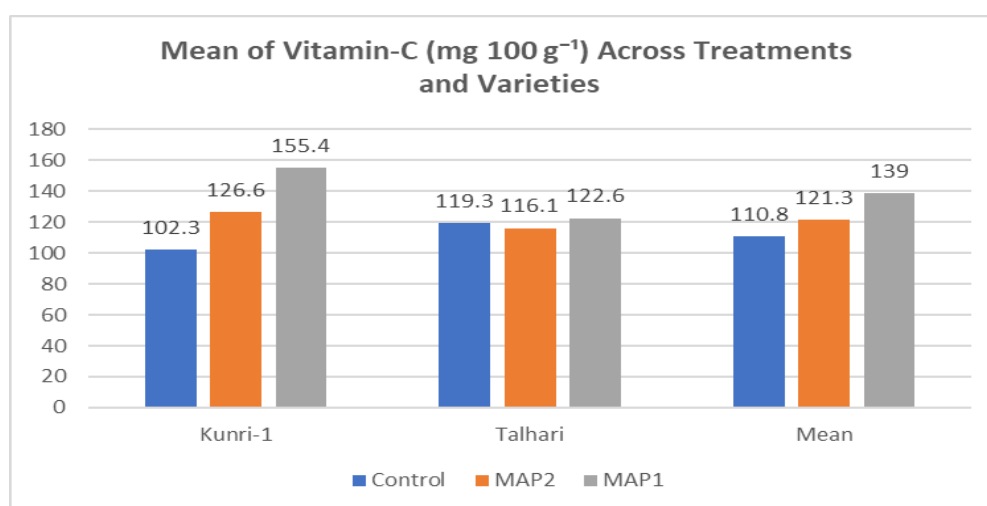


Figure 10. Mean of Vitamin C ($\text{mg } 100 \text{ g}^{-1}$) Across Treatments and Varieties at CS

Under cold storage (CS), vitamin C retention was significantly affected by packaging, variety, and storage duration. MAP1 treatment preserved the

highest vitamin C content ($139.02 \text{ mg } 100 \text{ g}^{-1}$), followed by MAP2 ($121.31 \text{ mg } 100 \text{ g}^{-1}$) (Figure 12). Variety Kunri-1 maintained higher vitamin C (128.09

mg 100 g⁻¹) than Talhari (119.32 mg 100 g⁻¹). Despite overall declines with time, MAP under cold storage effectively reduced nutrient losses.

Vitamin C is a nutritional characteristic of green chilies and is very susceptible to temperature, oxygen, and storage time. The observed ascorbic acid losses during storage can be explained as a result of oxidative deterioration and enhanced metabolic activity during ripening and senescence. MAP treatments were always more effective than the control in terms of vitamin C retention, which implied that lower oxygen and higher carbon dioxide concentration lowered the oxidation and respiration rates. Cold storage also increased the preservation of nutrients by reducing enzyme activity and decreasing physiological degradation. The increased retention with MAP1 implies that optimized gas composition is a major factor in ensuring nutritional integrity. In general, modified atmosphere

packaging together with low-temperature storage is viable in maintaining the nutritional value of chilies, especially vitamin C, in postharvest management and storage. Li et al. (2014), who have found that controlled atmospheres retain vitamin C by inhibiting oxidative metabolism.

Total Soluble Solids (TSS): Total soluble solids greatly depended on packaging and storage time at room temperature. Control fruits recorded a higher mean TSS (3.40 °Brix) compared to MAP (3.13 °Brix), indicating faster metabolic activity. Longi had a high TSS as compared to Talhari and Kunri-1. Elevated TSS levels in Longi may result from increased starch hydrolysis and sugar concentration due to higher respiration and ripening rates. TSS grew steadily with storage time in all treatments but MAP always moderated this growth indicating slowed ripening in the conditions of modified atmosphere.

Table 8: Mean of Total soluble solids (Brix) at RT

Treatment	Varieties			Mean
	Kunri-1	Talhari	Longi	
Control	2.5933	3.6867	3.9133	3.3978
MAP	2.6400	3.0500	3.6933	3.1311

In cold storage, variety and storage duration had a significant impact on TSS, but the effect of treatment was relatively minor. MAP2 recorded the highest mean TSS (3.74 °Brix), closely followed by control (3.72 °Brix) and MAP1 (3.66 °Brix). Kunri-1 exhibited

higher TSS (4.62 °Brix) than Talhari (Figure 10). TSS decreased slowly with storage time as compared to room temperature, implying the decrease in metabolic activity and slower sugar accumulation at cold temperatures

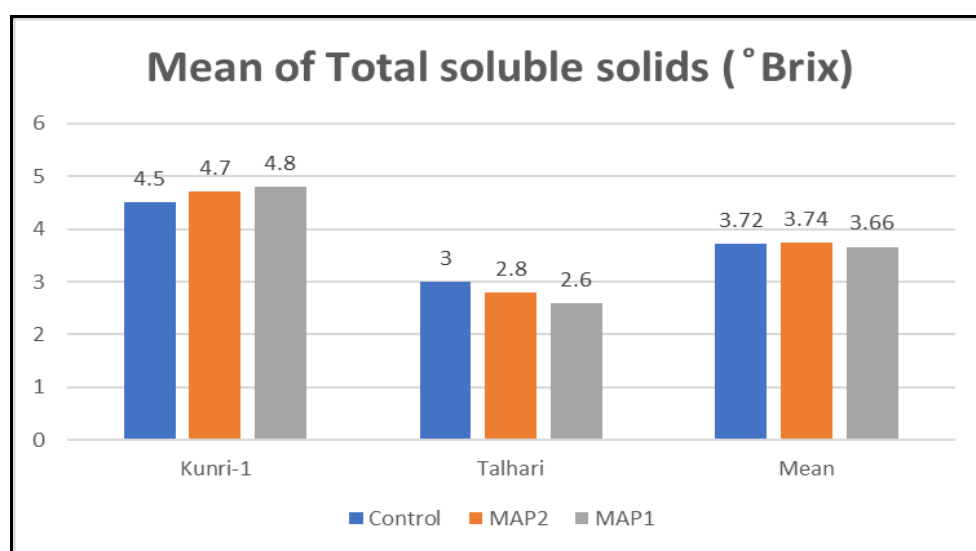


Figure 10. Mean of Total soluble solids (Brix) at CS

TSS variation indicated the variation in metabolic rate in different storage conditions. An increase in TSS at room temperature, especially in control fruits, implies increased respiration and sugar concentration, resulting in moisture loss. Cold storage, conversely, slowed down respiration, which caused slow dissolution of soluble solids. MAP treatment was used to stabilize TSS by inhibiting gas exchange and reducing

biochemical processes. Wasker et al. (1999) and Wills et al. (1981) had similar trends, which confirm that lower temperature and altered atmospheres are effective in retarding ripening and quality loss. Saltveit (2019) had reported similar stabilization of TSS in MAP-stored capsicum earlier.

Titrateable Acidity (TA): Packaging, variety, and duration of storage had a profound impact on titrateable acidity at room temperature. Chillies treated with MAP

had a higher mean acidity (0.23%) than control fruits (0.22%), meaning that organic acids are less metabolically degraded. Kunri-1 had the highest mean TA (0.25%), followed by Talhari (0.23%), and Longi (0.21%). Acid titratable rose steadily with time of storage in all varieties. The lowest TA was recorded at

the first stage, and maximum values were recorded at day 12, especially in Kunri-1. MAP treatment maintained elevated acidity levels compared to the control as an indication of delayed ripening and reduced respiratory loss

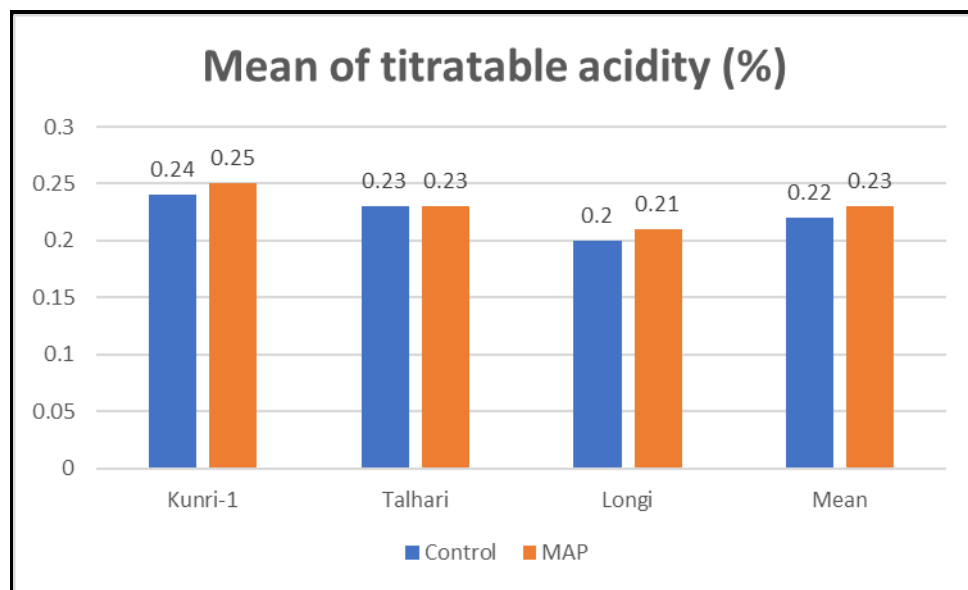


Figure 11. Mean of Titratable Acidity (%) Across Treatments at RT

Titratable acidity grew considerably with storage time and type under cold storage. The means of acidity were higher in MAP-treated fruits (0.51%) than in the control (0.47%). Variety Talhari had a greater level of

acidity (0.63%) than Kunri-1 (0.34%). Generally, cold storage with MAP resulted in a reduced metabolic rate and preservation of organic acid content during storage.

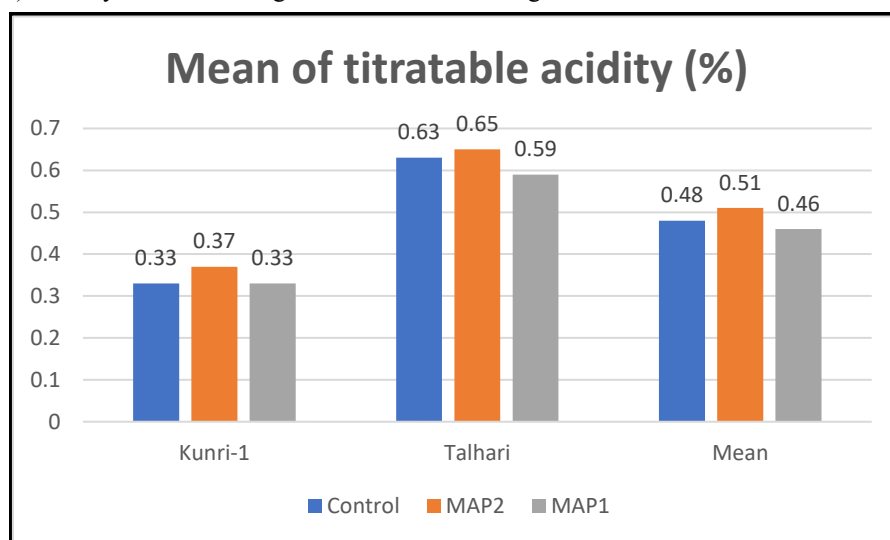


Figure 12. Mean Percentage of Titratable Acidity Across Treatments at CS

The progressive rise in titratable acidity during the storage period is a result of continued metabolic and enzymatic processes that are related to the process of fruit maturation and senescence. Increased acidity in MAP-treated chilies signifies low respiration and slow use of organic acids as respiratory substrates. Enzymes like pectin methyl esterase can also play a role in amplifying acid formation during ripening. Cold

storage also regulates metabolism, which could preserve acid more than it is at room temperature. These results are consistent with the findings of Yemelyanov et al. (2023) who proved that by retarding senescence low-oxygen modified atmosphere packaging preserve citric and malic acid levels.

pH Value: At room temperature, treatment, variety, and storage period did not significantly differ in terms

of fruit pH. In comparison, control fruit had a mean pH (5.67) and MAP-treated chilies had a mean pH (5.62) (Table 9). The pH was gradually increasing in all

samples during the storage process indicating a gradual decrease in acidity due to continuous metabolic activity in the storage.

Table 9: Mean of pH Across Treatments and Varieties at RT

Treatment	Varieties			Mean
	Kunri-1	Talhari	Longi	
Control	5.6500	5.7109	5.6500	5.6703
MAP	5.6460	5.5242	5.7160	5.6287

Conversely, in cold storage, varieties and storing time had a strong effect on pH. Control fruit showed the highest mean pH (5.76), followed by MAP1 (5.68) and

MAP2 (5.63) (Figure 13). Overall, pH value rose with storage time, which indicated a decrease in acidity with extended cold storage.

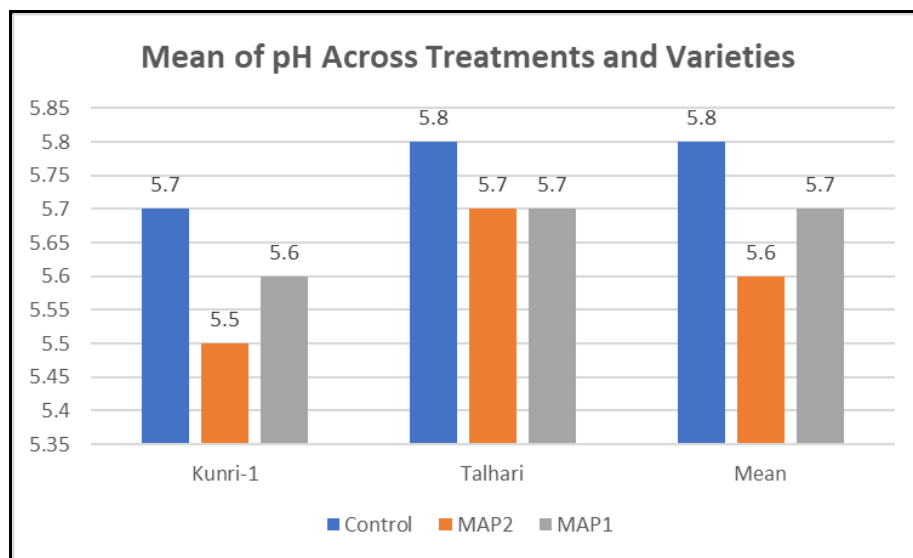


Figure 13. Mean pH Across Treatments and Varieties at CS

The progressive rise in pH during room and cold storage is strongly linked with a decrease in titratable acidity with the use of organic acids in respiration. MAP treatments always had slightly lower pH levels in comparison with control, indicating retarded metabolic activity by low oxygen availability. The cold storage also inhibited pH variations by retarding ripening activities. These findings resonate with research by Zhang et al. (2014), who found that low temperature and CO₂ enrichment preserves the acidity of fruit in storage and biochemical stability of chilies.

Phytochemical and Antioxidant Parameters

Total Phenolic Content (TPC) (mg GAE g⁻¹): The total phenolic content (TPC) gradually declined in all treatments and temperature and packaging had a strong effect. Treatment, varieties, storage days and their interactions played a significant role in total phenolic content at room temperature. Control fruit had a high mean of phenolics (156.62) than MAP-exposed chilies (143.23) (Table 10). Longi had a slightly higher phenolic content as compared to Talhari and Kunri-1 in both the control and packed treatments. The increase in phenols in all treatments was gradually related to storage time, suggesting that it accumulated as a result of stress during the ripening process and senescence.

Table 10. Phenolic Content (mg GAE g⁻¹) Across Treatments and Varieties at RT

Treatment	Varieties			Mean
	Kunri-1	Talhari	Longi	
Control	157.31	155.50	157.40	156.74
MAP	141.01	143.56	145.14	143.23

Under cold storage, total phenolics were significantly affected by treatment, varieties, and storage duration. MAP2 treatment maintained the highest mean phenolic content (150.72), followed by control (147.53) and

MAP1 (146.55) (Figure 14). Variety Kunri-1 showed higher phenolics than Talhari across the treatments, with phenolic levels increasing gradually during storage.

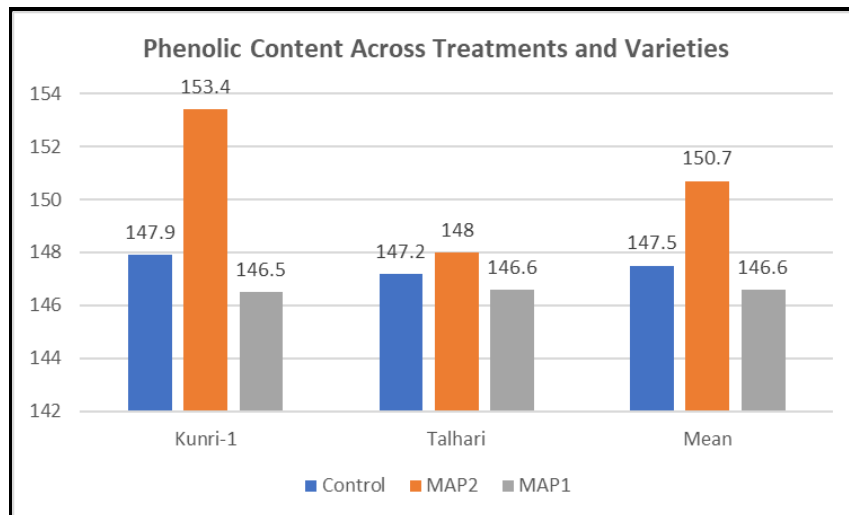


Table 14: Phenolic Content (mg GAE g⁻¹) Across Treatments and Varieties at CS

The perceived increase in the total phenolics throughout the storage can be explained by the intensification of the production of secondary metabolites in response to stress, especially those involving the flavonoid conversion pathways. At room temperature, the control fruit has more phenolics, which indicates increased metabolic and oxidative activities. On the other hand, existence of MAP2 lead to preservation of phenolic compounds under cold storage by regulating respiration and oxidative stress. In the context of Ren et al. (2024), which found that MAP reduces oxidative reactions by keeping oxygen

tension low, preserving antioxidant constituents (Ren et al., 2024), the findings correspond.

Antioxidant Activity (DPPH Assay): At room temperature, treatment, varieties, storage days, and their interaction had a significant influence on antioxidant capacity. Control fruits had a higher average antioxidant capacity (48.63) as compared to MAP-treated chilies (40.21). Longi had the highest mean of (55.34) then Kunri-1 (40.54) and Talhari (37.36) across the varieties. Antioxidant capacity rose steadily with the length of storage in all treatments, indicating the synthesis of protective compounds is enhanced during ripening and senescence

Table 11. Mean of anti-oxidant Across Treatments and Varieties at RT

Treatment	Varieties			Mean
	Kunri-1	Talhari	Longi	
Control	36.53	42.22	67.14	48.63
MAP	44.56	32.50	43.53	40.20

The treatment, varieties, and storage days and their interactions significantly varied the antioxidant capacity under cold storage. The maximum mean capacity was MAP1 (58.7), then control (52.6), and

MAP2 (50.2). In general, Kunri-1 had a greater anti-oxidant capacity than Talhari, and values rose steadily in storage (Figure 15).

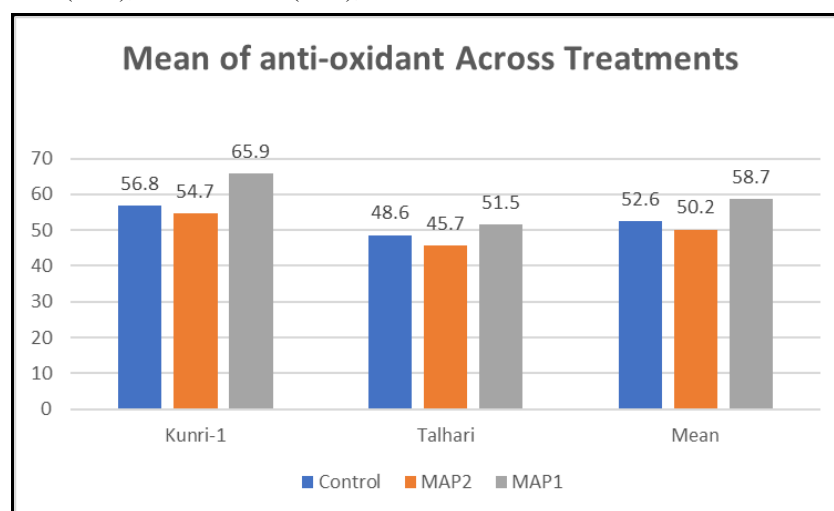


Figure 15: Mean antioxidant capacity across treatments and varieties at CS

The rise in antioxidant capacity over time of storage was a physiologic response to oxidative stress and metabolic fluctuation in the course of ripening. Increased control fruit values at room temperature suggest an increased rate of oxidation and stress-induced production of antioxidant compounds. On the other hand, at cold storage MAP, and MAP 1 in particular, preserved the antioxidant capacity better by inducing a slowing of respiration and reducing oxidative reactions. Low oxygen and high CO₂ probably inhibited the enzymatic degradation of antioxidants. These results indicate that MAP with cold storage is effective in preserving the functional and nutritional value of chilies. The observations on the stability of the antioxidant activity of MAP-stored fruits support the data reported by Ramakanth et al. (2024), who showed that minimal oxygen exposure is a key factor in extending radical scavenging activity in perishable vegetables.

CONCLUSION

Postharvest physiological, chemical, and phytochemical quality of green chilies is dramatically improved using Modified Atmosphere Packaging, especially under cold storage. MAP extends the shelf life of food by regulating the rate of respiration, moisture loss, and oxidative degradation and preserves the vital nutrients and antioxidants. The comparative design showed that the postharvest integrity depends on temperature management and atmospheric modification. The study therefore supports MAP as a sustainable, low-chemical treatment, which is able to minimize wastage, enhance the safety of food, as well as enhance value-chain performance in the horticultural industry. In general, the research has an important empirical and practical value and can inform industry practices and future research in postharvest technology.

AUTHORS' CONTRIBUTIONS

S. S: Conducted research, recorded data, wrote manuscript. **R. M. A. A:** Assisted in data recording and data analysis. **N. M:** Assisted in data recording. **H. M. K:** Assisted in manuscript writing and editing. **Saman Shabir:** Assisted in manuscript writing and data analysis. **I. A :** Reviewed the manuscript; technically assisted in editing and final review. **M.I:** Assisted in data recording.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest related to this manuscript.

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