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Effect of Calcium Chloride, Oil Coating, and Wrapping Materials on Quality and Shelf Life of Apple (*Malus* × *domestica* Borkh.)

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ABSTRACT

Apple is a strategic fruit crop in Afghanistan, produced in large quantities annually; however, postharvest losses during storage remain a major challenge both nationally and globally. This study aimed to evaluate effective and economically feasible coating treatments to maintain apple fruit quality during storage. The experiment was conducted in 2025 at the Horticulture Laboratory, Faculty of Agriculture, Kabul University, Afghanistan, to assess the effects of various coatings, wrapping materials, and CaCl2 on the shelf life of apple (cv. Golden Delicious). Seven treatments (control, aloe vera gel coating, polyethylene packaging, newspaper packaging, Cacl2 1.5%, Cacl2 3%, and sunflower oil coating) were arranged in a factorial CRD design with four replications. Key physicochemical and quality parameters, including TSS, reducing and total sugars, titratable acidity, firmness, weight loss, decay loss, and physiological loss weight (PLW), were measured over a 45-day storage period. Results indicated that both coating type and storage duration significantly influenced fruit quality. Sunflower oil coating (T7) demonstrated superior performance by maintaining biochemical stability and minimizing weight loss (416.34), PLW (48.08) and decay (416.34), followed by aloe vera gel (T2), which also preserved chemical properties and reduced losses. Conversely, polyethylene packaging (T3) and 3% CaCl2 (T6) showed the highest deterioration in quality attributes. Overall, edible coatings effectively reduced respiration, moisture loss, and metabolic activity, thereby extending shelf life. Based on these findings, sunflower oil and aloe vera gel are recommended as cost-effective postharvest treatments. Further research is suggested to evaluate their effectiveness on freshly harvested fruits of other apple cultivars under different storage conditions.

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INTRODUCTION

Apple (*Malus domestica* Borkh.), a member of the Rosaceae family, is one of the most widely cultivated and consumed temperate fruit crops worldwide, with substantial nutritional, economic, and cultural importance (Kumar et al., 2024; Patocka et al., 2020). In Afghanistan, apples are among the most important fruit crops and rank second only to grapes in terms of production. Its cultivation has expanded significantly in recent years, reflecting its growing role in the national horticultural economy. According to FAOSTAT (2022), apples were grown on approximately 30,163 hectares in 2022, producing about 318,402 metric tons with an average yield of 10,556 kg ha^{-1}. Apples are highly valued for their versatility and rich nutritional composition. Nearly all parts of the fruit, except the seeds, are edible and widely processed into products such as juices, cider, jams, dried slices, and other value-added foods. They are rich in bioactive compounds that support human health by enhancing immunity, reducing oxidative stress, and promoting overall well-being. Scientific evidence confirms that apples contain significant levels of phytochemicals, vitamins, and antioxidants that contribute to their health-promoting properties (Balík et al., 2023; Millán-Laleona et al., 2023).

Apples contain moderate carbohydrates, mainly natural sugars, while remaining low in fat and protein. They are composed of approximately 84–86% water, contributing to their refreshing and hydrating properties. They also provide dietary fiber (2.0–2.97 g per 100 g), along with essential minerals such as potassium, calcium, magnesium, and phosphorus, and vitamins including vitamin C and B-complex vitamins. In addition, apples are rich in phytochemicals like quercetin, catechin, chlorogenic acid, and phloridzin, which exhibit strong antioxidant activity and are associated with reduced risks of chronic diseases, including cardiovascular disorders, diabetes, and certain cancers (Arnold & Gramza-Michalowska, 2024; Patocka et al., 2020). Beyond fresh consumption, apples also have significant industrial value. Apple pomace is a valuable source of dietary fiber for food formulations. At the same time, apple pectin is widely used as a gelling, stabilizing, and thickening agent in the food, pharmaceutical, and packaging industries. Apple-derived products, such as juice and cider vinegar, have also attracted attention for their functional and medicinal properties, particularly their antioxidant activity and potential health benefits (Marcotte et al., 2022; Baker et al., 2025).

Postharvest interventions like $CaCl_2$, edible coatings, and protective wrapping materials have gained considerable attention as effective strategies to prolong the shelf life and preserve apple quality (Bhat et al., 2023). Research has shown that $CaCl_2$ can improve apple storage quality by strengthening cell wall structure, reducing weight loss, maintaining fruit firmness, and delaying ripening. Its application after harvest, or in combination with other gases and compounds, has been reported to reduce decay and enhance both physical and biochemical properties of apples (Gemeda, 2021; Beiparysa et al., 2023). In addition, preharvest application of $CaCl_2$ has also been found effective in improving firmness and overall storage performance (Rilak et al., 2023). On the other hand, modern edible coatings and packaging systems such as shrink films, biodegradable polymers, and Modified Atmosphere Packaging (MAP) play an important role in reducing moisture loss, controlling respiration, lowering ethylene production, and slowing down fruit senescence. By creating a controlled microenvironment around the fruit, these technologies help preserve texture, color, flavor, and nutritional quality during storage (Sharma et al., 2013; Kumar & Sethi, 2021). Scientific evidence suggests that integrating calcium-based treatments with advanced coating and packaging technologies offers an effective strategy to reduce postharvest losses and extend the shelf life of apples under different storage conditions (Dilmaçünal & Yiğit, 2023; Azadbakht et al., 2026).

Despite high production potential, post-harvest losses remain a major challenge in apple-producing regions, including Afghanistan. Inadequate harvesting, handling, storage, and transportation practices often result in significant quality deterioration and economic losses. Seasonal price fluctuations further worsen the situation, with prices dropping during harvest periods and increasing during off-seasons. Post-harvest losses can reach up to 31% at farm level and even higher along the supply chain (Masood, 2011; Hasan et al., 2024).

Apples are highly perishable fruits, and their post-harvest quality rapidly declines due to respiration, moisture loss, and microbial decay, especially in regions with limited storage facilities. This creates a major problem of post-harvest losses, reduced market value, and poor fruit quality. Although treatments such as calcium chloride, edible oil coatings, and wrapping materials have shown potential to improve firmness, reduce weight loss, and extend shelf life, there is still a clear research gap in understanding their comparative effectiveness and combined influence under local storage conditions. Therefore, this study is important for developing simple, low-cost post-harvest technologies to reduce losses and improve fruit quality, particularly in areas lacking cold storage infrastructure (Hasan et al., 2024; Dilmaçünal & Yiğit 2023). The main goal of this study is to evaluate the effects of calcium chloride, oil coatings, and wrapping materials on the physicochemical quality, storage life, and shelf stability of Golden Delicious apples, and to compare their effectiveness in reducing decay and physiological weight loss.

According to the goals of the research, the following alternative hypothesis was formulated: There are significant differences among Cacl2, oil coating, and wrapping materials in their impacts on shelf life, physicochemical quality, and postharvest losses of apples during storage, with at least one treatment showing superior performance compared to others and the control.

Accordingly, the study addresses the following research questions:

- How do Cacl2, oil coating, and wrapping materials differ in their effects on physicochemical characteristics of apples during storage?
- Which postharvest treatment (Cacl2, oil coating, or wrapping material) is most effective in extending shelf life and minimizing post-harvest losses?

METHODS AND MATERIALS

This section provides a comprehensive description of the study's temporal and spatial context, including the time and location where the experiment was conducted. It also presents detailed information on the materials utilized and the experimental design employed for statistical analysis. In addition, the section clearly outlines the treatments applied, the parameters measured, and the methodologies adopted for data collection and analysis.

Research Site

The present research was carried out in the Department of Horticulture, Faculty of Agriculture, Kabul University, Afghanistan, during November and December 2025, in the Jamala Mina area of Kabul. The experiment was carried out in a lab with an average temperature of 10–15 °C and a relative humidity of 50–60. Various types of edible coatings were applied to apple fruits to evaluate their effectiveness in preserving postharvest quality and extending shelf life. The findings of this study are intended to provide scientifically validated recommendations for the selection of the most effective coating treatments for orchardists and farmers.

Instruments

In this study, Golden Delicious apples were used, obtained from local markets in Kabul. The materials used for the coating treatments included polyethylene plastic, newspaper sheets, aloe vera gel, sunflower oil, and calcium chloride, all purchased from local markets in Kabul. These materials were selected based on their availability and previous use in edible and protective coatings for postharvest fruit preservation.

Research Design and Treatments

The present study was designed using a factorial Completely Randomized Design (CRD), comprising seven treatments with four replications. The storage duration was set at 45 days, and 800 g of apples were used per replication in each treatment. All apples were selected to be uniform in weight, shape, color, and physical characteristics, and were free from any disease or physical damage. Detailed information regarding the experimental setup is presented in Table 1.

Table 1. *Experimental details.*

Treatment	Coating Types	Quantity of Apples $_{(g)}$	Duration $_{(Days)}$	Design
T_1	Control			
T_2	Aloe vera gel Coating			
T_3	Polythene packaging			
T_4	Newspaper packaging	800	45	Factorial CRD
T_5	Calcium chloride 1.5%			
T_6	Calcium chloride 3%			
T_7	Sunflower oil Coating			

In this study, various edible coatings were employed to extend the shelf life of apple fruits, focusing on readily accessible, cost-effective materials. These coatings have been applied in different countries in various forms and concentrations, demonstrating their widespread use and effectiveness in postharvest fruit preservation. The specific coating materials used in the experiment included polyethylene plastic, newspaper sheets, aloe vera gel, sunflower oil, and calcium chloride, all of which were selected based on their availability, cost-effectiveness, and previously reported efficacy in maintaining postharvest fruit quality (Azadbakht et al., 2026; Solhjoo et al., 2023; Xin et al., 2023).

Coating Preparation

Aloe vera leaves were first sorted to exclude any with dents or physical damage, and followed by a thorough tap water wash. After gently removing the thorns, the outer leaf cortex was peeled away to reveal the inner mucilaginous gel (Álvarez-Barreto et al., 2023). The calcium chloride coating was prepared by dissolving calcium chloride in distilled water, while sunflower oil was procured from local markets.

Measured Parameters

In this study, several parameters were evaluated to determine the effects of different coating treatments on the shelf life of apple fruits. These included TSS, reducing sugar (RS), non-reducing sugar (NRS), total sugar (TS), titratable acidity (TA), firmness, weight per treatment, decay loss, and PLW. The measurement of these parameters enabled a comprehensive assessment of the impact of various edible coatings on postharvest quality, storage stability, and overall shelf life of apples. The methods for measuring each parameter are described below.

To determine the total soluble solids (TSS) of the fruit, the pulp was first extracted and then measured using a hand digital refractometer. The obtained data were recorded and preserved for subsequent analysis.

In order to determine RS Phenolphthalein was utilized as an indicator, and 25 mL of the fruit nectar was combined with 100 mL of distilled water. 1 N sodium hydroxide (NaOH) was used to neutralize the solution. After adding 2 mL of a 45% lead acetate solution, the mixture was briskly shaken and left to stand for 10 minutes. Next, two mL of a 22% potassium oxalate solution were added. After adding distilled water to get the total volume down to 250 mL, the mixture was filtered through Whatman No. 1 filter paper. Using methylene blue as an indicator, an aliquot of 10 mL of the filtrate was titrated against Fehling's mixture (5 mL Fehling A + 5 mL Fehling B) (Ranganna, 1986).

$$\textbf{Reducing sugars}\ (\%) = \frac{\text{mg of invert sugar} \times \text{Dilution} \times 100}{\text{Titer} \times \text{Volume of sample} \times 100}$$

Since sucrose constitutes the major portion of NRS in nectar, its content was calculated as follows:

$$\textbf{NRS = TS – RS}$$

In TS, 50 mL of the filtered RS solution, 5 g of citric acid, and 50 mL of distilled water were combined, and the mixture was heated for 10 minutes to determine the TS.

Phenolphthalein was used as an indicator to neutralize the solution with 1 N NaOH once it had cooled. After filtering and adjusting the volume to 250 mL with distilled water, 10 mL aliquots were titrated against Fehling's solution (5 mL Fehling A + 5 mL Fehling B) using methylene blue as an indicator (Ranganna, 1986).

$$\textbf{Total sugars}\ (\%) = \frac{\text{mg of invert sugar} \times \text{Dilution} \times 100}{\text{Titer} \times \text{Volume of sample}}$$

A known volume of nectar diluted with deionized water and titrated against 0.1 N NaOH using phenolphthalein as an indicator. The titratable acidity was expressed as a percentage of malic acid (Ranganna, 1986).

$$\textbf{Titratable Acidity}(\%) = \frac{\text{Titer} \times \text{Normality of alkali} \times \text{Volume made up} \times \text{Equivalent weight of acid} \times 100}{\text{Volume of sample} \times \text{Volume of aliquot} \times 1000}$$

Fruit firmness was measured using a digital fruit penetrometer and expressed in kilograms per square centimeter (kg/cm²). The weight of the fruits was accurately determined using a digital balance, and the data were recorded in **grams (g)** for subsequent analysis.

$$\textbf{Weight}\ \boldsymbol{Losses} = \text{Initial total fruit weight (g)} - \text{Final total fruit weight (g)}$$

Decay loss (%) represents the proportion of fruits that have spoiled or deteriorated during the storage or experimental period. It is calculated using the weight of decayed fruits (g) relative to the initial total fruit weight (g), which is the total weight of all fruits at the beginning of the experiment or storage period. The resulting value expresses the percentage of fruit loss due to decay. This method is widely employed in postharvest studies to quantify fruit spoilage and to evaluate the effectiveness of different storage conditions, treatments, or coating materials (Siroha et al., 2026).

$$\textbf{Decay Loss}(\%) = \frac{\text{Weight of decayed fruits (g)}}{\text{Initial total fruit weight (g)}} x\ 100$$

Physiological Loss in Weight (PLW) is used to evaluate the weight reduction of fruits or vegetables during storage due to physiological processes such as respiration and transpiration. The PLW (%) is calculated by comparing the initial weight of the produce at the beginning of storage with the final weight measured later, and then expressing the difference relative to the initial weight as a percentage (Siroha et al., 2026).

$$\textbf{PLW}\ (\%) = \frac{\text{Initial weight (g)} - \text{Final weight (g)}}{\text{Initial weight (g)}}\ x\ 100$$

In this formula, the initial weight is the weight of the fruits/produce at the start of the experiment, and the final weight is the weight after a defined storage period. This method is widely used in postharvest quality assessments to quantify weight loss caused by normal physiological processes during storage and handling.

Data Analyses

Data for each parameter were recorded at four time points: 0 (initial), 15, 30, and 45 days. The experiment was arranged in a factorial CRD design, with the first factor comprising the different coating treatments and the second factor the storage duration. The collected Data were analyzed by factorial analysis of variance (ANOVA) in STAR software. Significant differences among treatments were considered at $P \leq 0.05$ and $P \leq 0.01$. Mean comparisons were made using the Least Significant Difference (LSD) test at the respective levels of significance. In the results, treatments were labelled with lowercase letters within columns (coating) and uppercase letters within rows (storage period) to indicate statistically significant differences among means (Kazemzadeh Pournaki et al., 2024).

FINDINGS

The research results are systematically presented across 9 parameters in well-structured, clearly organized tables. Each table is comprehensively described and interpreted to ensure clarity, facilitate accurate understanding, and enable readers and stakeholders to use the study's results effectively.

TSS

The effects of seven edible coating treatments and storage duration on the TSS of apple fruit were evaluated over 45 days of storage. Analysis of variance showed that both coating treatments and storage periods had highly significant effects on TSS ($P \leq 0.01$). But interaction between coating type and storage duration was not statistically significant, indicating that the pattern of TSS changes over time was generally consistent across treatments Table 2.

Table 2. *Effect of edible coating and storage period on TSS (Brix) of apple.*

Factor A	Factor B				Factor A Means
	Initial	15 Days	30 Days	45 Days	
T_1	10.45	11.55	13.05	13.75	**12.20** ^{bc}
T_2	12.88	13.00	13.25	15.00	**13.53** ^{a}
T_3	9.95	12.50	14.00	14.38	**12.71** ^{ab}
T_4	9.75	10.80	11.73	12.50	**11.19** ^{d}
T_5	10.25	11.63	12.25	13.75	**11.97** ^{bcd}
T_6	9.88	10.63	11.50	14.43	**11.61** ^{cd}
T_7	10.50	11.48	12.00	14.00	**11.99** ^{bcd}
Factor B Means	**10.52** D	**11.65** C	**12.54** B	**13.97** A	

Factors	F- test	LSD (0.01)	CV
Factor A	**	0.99	
Factor B	**	0.76	8.81
A x B	Ns	-	

Factor A: *Edible coating;* ***Factor B:*** *Storage period;* ***A × B:*** *Interaction between factors;* ***NS:*** *Not significant;* *****:*** *Significant at P ≤ 0.01;* ***LSD:*** *Least Significant Difference;* ***CV:*** *Coefficient of Variation. Within each column, means followed by different lowercase letters (a, b, c, ...) are significantly different according to the LSD test (P ≤ 0.05). Within each row, means followed by different uppercase letters (A, B, C, ...) are significantly different according to the LSD test (P ≤ 0.05).*

A progressive increase in TSS was observed with increasing storage duration. To determine the magnitude of change within each treatment, the initial TSS value was subtracted from the corresponding value recorded at 45 days of storage. The largest increase in TSS was observed in Treatment 6 (4.55), while the smallest was in Treatment 2 (2.13). Furthermore, relatively lower changes were also noted in Treatments 4 and 7, with increases of 2.75 and 3.50, respectively. Based on the LSD mean-comparison test, means followed by identical lowercase letters within the same column or identical uppercase letters within the same row did not differ significantly, confirming the statistical grouping of treatments and storage intervals.

Reducing Sugar (RS)

The finding demonstrated that storage period and different coating treatments had a highly significant effect ($P \leq 0.01$) on the RS content of apple fruits. However, the interaction between storage duration and coating treatments was not statistically significant Table 3.

Table 3. *Effect of edible coating and storage duration on RS of apple (%).*

Factor A	Factor B				Factor A Means
	Initial	15 Days	30 Days	45 Days	
T_1	4.88	5.43	8.33	9.20	**6.96** ab
T_2	5.20	6.70	8.43	10.20	**7.63** a
T_3	4.73	6.35	8.40	9.73	**7.30** ab
T_4	4.05	5.35	6.73	8.43	**6.14** c
T_5	4.78	6.05	7.28	9.08	**6.79** bc
T_6	4.35	5.90	6.98	9.73	**6.74** bc
T_7	5.35	6.18	6.60	8.18	**6.58** bc
Factor B Means	**4.76** D	**5.99** C	**7.53** B	**9.22** A	

Factors	F- test	LSD (0.01)	CV
Factor A	**	0.75	
Factor B	**	0.57	11.68
A x B	Ns	-	

The findings further revealed that the greatest variation in RS content was observed in treatment 3, where the value increased from 4.72 to 9.72. In contrast, the lowest variation was observed in treatment 7, where the RS content increased from 5.35 to 8.17. Moreover, with respect to storage duration, the lowest RS content was observed at the initial stage (4.76), whereas the highest value was recorded after 45 days of storage (9.22).

Non-Reducing Sugar (NRS)

Regarding NRS, the study found that different coating treatments did not significantly affect the NRS content of apple fruits. However, as storage time progressed, the NRS content of the fruits decreased significantly. Furthermore, no significant interaction was observed between storage duration and the different coating treatments Table 4.

Table 4. *Impact of edible coating and storage duration on NRS of apple (%).*

Factor A	Factor B				Factor A Means
	Initial	15 Days	30 Days	45 Days	
T_1	3.98	3.78	3.53	3.30	**3.64**
T_2	4.63	3.93	3.65	3.30	**3.88**
T_3	3.90	3.68	3.45	3.18	**3.55**
T_4	4.15	3.85	3.70	3.03	**3.68**
T_5	3.95	3.75	3.70	3.38	**3.69**
T_6	4.28	3.75	3.60	3.20	**3.71**
T_7	3.78	3.58	3.50	3.43	**3.57**
Factor B Means	**4.09** A	**3.76** B	**3.59** B	**3.26** C	

Factors	F- test	LSD (0.01)	CV
Factor A	Ns	-	
Factor B	**	0.24	9.26
A x B	Ns	-	

The finding also revealed that the lowest variation in NRS was recorded in treatment 7, where the value decreased from 3.78 to 3.43; while, no significant variance was observed among the treatments. Moreover, over the storage period, NRS content decreased from 4.09 to 3.26, indicating that storage duration significantly affected it.

Total Sugar (TS)

Different coating treatments and storage duration showed an extremely significant effect ($P \leq 0.01$) on the TS content of apple fruits Table 5. The results indicated that TS content increased progressively with storage time. The lowest TS content was documented at the primary stage (8.85%), whereas the highest value was detected after 45 days of storage (12.48%).

Table 5. *Impact of edible coating and storage duration on TS of apple (%).*

Factor A	Factor B				Factor A Means
	Initial	15 Days	30 Days	45 Days	
T_1	8.85	9.20	11.85	12.50	**10.60** ^{b}
T_2	9.83	10.63	12.08	13.50	**11.51** ^{a}
T_3	8.63	10.03	11.85	12.90	**10.85** ^{ab}
T_4	8.20	9.20	10.43	11.45	**9.82** ^{c}
T_5	8.73	9.80	10.98	12.45	**10.49** ^{bc}
T_6	8.63	9.65	10.58	12.93	**10.44** ^{bc}
T_7	9.13	9.75	10.10	11.60	**10.14** ^{bc}
Factor B Means	**8.85** D	**9.75** C	**11.12** B	**12.48** A	

Factors	F- test	LSD (0.01)	CV
Factor A	**	0.75	
Factor B	**	0.57	7.66
A x B	Ns	-	

The findings further revealed that treatment 7 was the most stable, with the lowest variation, and that TS content increased from 9.13% to 11.60%. In contrast, the greatest variation was observed in treatment 3, where TS content increased from 8.63% to 12.90%.

Titratable Acidity (TA)

Titratable acidity of apple fruits was also significantly affected by storage duration (P ≤ 0.01) during the course of the study. However, the results indicated that different coating treatments did not have a significant effect on the TA of the fruits, and no significant collaboration was observed among coating treatments and storage duration Table 6.

Table 6. *Effect of edible coating and storage period on apple acidity (%).*

Factor A	Factor B				Factor A Means
	Initial	15 Days	30 Days	45 Days	
T_1	0.184	0.151	0.151	0.134	**0.155**
T_2	0.184	0.168	0.151	0.134	**0.159**
T_3	0.201	0.168	0.151	0.134	**0.163**
T_4	0.201	0.168	0.168	0.168	**0.176**
T_5	0.201	0.184	0.151	0.151	**0.172**
T_6	0.218	0.168	0.168	0.168	**0.180**
T_7	0.168	0.168	0.168	0.151	**0.163**
Factor B Means	**0.194** A	**0.168** B	**0.158** B	**0.148** B	

Factors	F- test	LSD (0.01)	CV
Factor A	Ns	-	
Factor B	**	0.025	21.12
A x B	Ns	-	

The findings showed that TA decreased with increasing storage time. The maximum TA was recorded at the primary stage (0.194%), while the lowest value was detected after 45 days of storage (0.148%). Although different coating treatments did not exert a significant effect, the lowest variation was observed in treatment 7, where titratable acidity decreased from 0.168% to 0.151%. In contrast, the greatest variation occurred in treatment 3, where titratable acidity declined from 0.201% to 0.134%.

Firmness

The results of the study indicated that different coating treatments and storage duration had a highly significant effect (P ≤ 0.01) on apple fruit firmness. Moreover, a significant collaboration between coating treatments and storage duration was also detected Table 7.

Table 7. *Effect of edible coating and storage period on apple firmness (Kgf).*

Factor A	**Factor B**			
	Initial	**15 Days**	**30 Days**	**45 Days**
T_1	$7.50^{a}{}_{A}$	$6.88^{ab}{}_{B}$	$6.43^{a}{}_{B}$	$4.03^{bc}{}_{C}$
T_2	$7.50^{a}{}_{A}$	$7.08^{a}{}_{A}$	$6.43^{a}{}_{B}$	$5.78^{a}{}_{C}$
T_3	$7.50^{a}{}_{A}$	$5.15^{c}{}_{B}$	$4.85^{d}{}_{B}$	$3.65^{cd}{}_{C}$
T_4	$7.50^{a}{}_{A}$	$4.58^{d}{}_{B}$	$4.33^{e}{}_{BC}$	$3.99^{bc}{}_{C}$
T_5	$7.50^{a}{}_{A}$	$6.50^{b}{}_{B}$	$5.41^{c}{}_{C}$	$3.98^{bc}{}_{D}$
T_6	$7.50^{a}{}_{A}$	$6.65^{ab}{}_{B}$	$3.57^{f}{}_{C}$	$3.23^{d}{}_{C}$

T₇	7.50^{a}_{A}	6.80^{ab}_{B}	5.95^{b}_{C}	4.25^{b}_{D}

Factors	F-test	LSD (0.01)	CV
Factor A	**	-	
Factor B	**	-	4.32
A x B	**	0.47	

Kgf: kilogram-force.

The finding further showed that after 15 days of storage, the least change in fruit firmness was observed in treatments 2, 1, 7, and 6, respectively. According to the LSD test, treatments 1, 2, 7, and 6 did not differ significantly from each other. In contrast, the greatest changes in firmness were recorded in treatment 3. After 30 days of storage, the lowest changes were observed in treatments 1, 2, and 7. Based on the LSD test, treatments 1 and 2 were not significantly different and were grouped in group A, while treatment 7 was placed in group B. However, the greatest change at 30 days was observed in treatment 6. At 45 days of storage, the lowest changes in fruit firmness were observed in treatments 1 and 7. According to the LSD test, treatment 2 was classified in group A, while treatments 7, 1, 4, and 5 were placed in group B. The greatest changes in firmness were observed in treatment 6 at this stage.

Weight Losses

Fruit weight losses of apple was significantly affected by different coating treatments and storage duration (P ≤ 0.01) during the experiment, and a significant collaboration between storage duration and coating treatments was also detected Table 8.

Table 8. *Impact of edible coating and storage period on weight of apple (g).*

Factor A	Factor B				Factor A Means
	Initial	15 Days	30 Days	45 Days	
T_1	-	158.94	274.40	454.48	295.94^{cd}
T_2	-	191.98	302.12	467.12	320.41^{bcd}
T_3	-	275.18	404.10	550.24	409.84^{a}
T_4	-	187.36	294.22	462.08	314.55^{bcd}
T_5	-	232.48	339.16	499.72	357.12^{abc}
T_6	-	260.44	356.52	509.24	375.40^{ab}
T_7	-	144.20	262.54	416.34	274.36^{d}
Factor B Means	-	**207.23** C	**319.01** B	**479.89** A	

Factors	F- test	LSD (0.01)	CV
Factor A	**	71.30	
Factor B	**	30.27	19.61
A x B	Ns	-	

The results indicated that at the initial stage, the fruit weight losses in all treatments were constant (0 g). However, after 15 days of storage, significant changes in fruit weight losses were recorded. The highest reduction was observed in treatment 3, where fruit weight decreased 275.18g, whereas the lowest reduction occurred in treatment 7, where fruit weight decreased 144.20g. After 30 days of storage, the greatest weight loss was again observed in treatment 3, while the lowest reduction was recorded in treatment 7. Similarly, after 45 days of storage, the highest reduction was observed in treatment 3, where fruit weight decreased

409.84 g, whereas the lowest reduction was recorded in treatment 7, where fruit weight decreased 274.36 g.

Decay Loss

The experiment conducted over a 45-day storage period showed, based on statistical analysis, that storage duration had a highly significant effect ($P \leq 0.01$) on decay loss of apple fruits. However, different coating treatments did not have a significant effect on decay loss, and no significant interaction was observed between storage duration and coating treatments Table 9.

Table 9. *Effect of edible coating and storage period on apple decay loss (%).*

Factor A	Factor B				Factor A Means
	Initial	15 Days	30 Days	45 Days	
T_1	-	3.27	3.80	7.55	**4.87**
T_2	-	3.23	3.79	6.59	**4.54**
T_3	-	4.27	7.74	11.50	**7.84**
T_4	-	3.77	3.74	6.64	**4.72**
T_5	-	3.05	4.05	7.48	**4.86**
T_6	-	3.35	3.56	6.72	**4.54**
T_7	-	3.38	3.95	3.97	**3.77**
Factor B Means	-	**3.47** AB	**4.38** AB	**7.21** A	

Factors	F- test	LSD (0.01)	CV
Factor A	Ns	-	
Factor B	**	4.83	180.85
A x B	Ns	-	

During storage, the lowest decay loss was recorded after 15 days (3.47%), whereas the highest was observed after 45 days (7.21%). Although the coating treatments did not significantly affect decay loss, the lowest was still recorded in treatment 7 (3.77%), while the highest was observed in treatment 3 (7.84%).

PLW

The results of the data analysis indicated that storage duration and different coating had a significant effect ($P \leq 0.01$) on the physiological loss in weight (PLW) of apple fruits during the 45-day storage period. Moreover, a significant interaction between storage duration and coating treatments was also observed Table 10.

Table 10. *Effect of edible coating and storage period on PLW of apple (%)*

Factor A	Factor B			
	Initial	15 Days	30 Days	45 Days
T_1	-	16.60 ^{de} C	30.50 ^{cd} B	49.27 ^{c} A
T_2	-	20.77 ^{c} C	33.98 ^{bc} B	51.80 ^{bc} A
T_3	-	23.08 ^{bc} C	37.15 ^{ab} B	53.34 ^{ab} A
T_4	-	19.65 ^{cd} C	33.04 ^{c} B	51.12 ^{bc} A
T_5	-	26.02 ^{ab} C	38.35 ^{a} B	54.99 ^{ab} A
T_6	-	29.21 ^{a} C	41.01 ^{a} B	56.93 ^{a} A
T_7	-	14.65^{e} C	28.87 ^{d} B	48.08 ^{c} A

Factors	F-test	LSD (0.01)	CV
Factor A	**	-	
Factor B	**	-	8.02
A x B	**	4.05	

The results further showed that after 15 days of storage, the maximum PLW was documented in treatment 6 (29.21%), while the lowest value was observed in treatment 7 (14.65%). After 30 days of storage, the maximum PLW was again observed in treatment 6 (41.01%), while the lowest value was recorded in treatment 7 (28.87%). Similarly, after 45 days of storage, the highest PLW was observed in treatment 6 (56.93%), whereas the lowest was in treatment 7 (48.08%).

DISCUSSION

A general increase in TSS, RS, and TS was observed throughout storage, while NRS and titratable acidity showed a declining trend. Among treatments, calcium chloride (T6) generally induced higher increases in soluble solids and sugars, whereas aloe vera gel (T2) and sunflower oil (T7) were more effective in moderating these changes. The increase in TSS and sugars is primarily associated with starch degradation, conversion of protopectin into soluble forms, and continuous metabolic activity during ripening and storage. These processes enhance soluble sugar concentration, thereby increasing sweetness and overall TSS levels. Similar observations have been reported by Zhang et al. (2024), Rilak et al. (2023), Mahnoor et al. (2024), and Tarawneh et al. (2025), who emphasized the role of storage conditions and coatings in regulating carbohydrate metabolism in apples.

RS increased steadily during storage, mainly due to enzymatic hydrolysis of starch into glucose and fructose mediated by α-amylase and β-amylase. Coated fruits exhibited a slower increase, indicating that edible coatings can effectively suppress metabolic activity by reducing respiration and ethylene production (Nisar et al., 2015; Deng et al., 2025). Conversely, NRS declined over time due to their conversion into RS, particularly sucrose hydrolysis, reflecting ongoing metabolic transformations within fruit tissues.

Titratable acidity decreased progressively during storage, a common physiological response in climacteric fruits such as apples. This reduction is mainly due to the utilization of malic acid, as substrates in respiration. The breakdown of organic acids into simpler compounds, including sugars, contributes to changes in taste and flavor. Although coating treatments did not significantly affect Titratable acidity, sunflower oil (T7) showed better retention of acidity, likely due to its barrier properties, which reduce gas exchange and metabolic activity. These results are consistent with earlier studies reporting that low temperature and edible coatings help delay acid degradation by reducing respiration rates (Mahnoor et al., 2024; Rilak et al., 2023; Zhang et al., 2024).

Fruit firmness declined significantly during storage, reflecting the progressive breakdown of cell wall components, including pectin, cellulose, and hemicellulose. This softening process is closely associated with enzymatic activity and conversion of protopectin into soluble pectin. Among treatments, aloe vera gel (T2) and sunflower oil (T7) were more effective in maintaining firmness, which may be attributed to their ability to form semi-permeable coatings that reduce moisture loss and slow down enzymatic degradation. Comparable findings have been reported in previous studies emphasizing the role of edible coatings in maintaining structural integrity and delaying softening processes (Mahnoor et al., 2024; Tarawneh et al., 2025).

Weight loss, including physiological weight loss, increased steadily during storage, mainly due to transpiration and respiration. Moisture loss remains the primary driver of postharvest weight reduction, while carbon loss through respiration further contributes to total weight decline. Coated fruits, particularly those treated with sunflower oil (T7), showed significantly lower weight loss and PWL, indicating improved moisture retention and reduced metabolic activity. These results agree with previous studies demonstrating that edible coatings effectively reduce water vapor transmission and respiration rates, thereby maintaining fruit mass and quality (Xin et al., 2023; Zhang et al., 2024; Rilak et al., 2023).

Decay loss increased continuously with storage duration, primarily due to the proliferation of fungal pathogens such as molds and yeasts. Although coating treatments did not show statistically significant differences, sunflower oil (T7) exhibited comparatively lower decay levels, suggesting partial antimicrobial or barrier effects. In contrast, polyethylene packaging (T3) showed higher decay incidence, possibly due to condensation and enhanced microbial growth under limited ventilation. These findings align with earlier reports indicating that postharvest decay is strongly influenced by storage duration, environmental conditions, and microbial activity (Mahnoor et al., 2024; Zhang et al., 2024).

A notable limitation of the present study was that data collection and sample evaluation were conducted approximately one month after the apple harvest season. Consequently, certain quality parameters may have been influenced by postharvest storage conditions and handling practices. Future research should commence immediately following harvest to better capture the intrinsic physicochemical and quality characteristics of freshly harvested apples and to minimize potential storage-related effects.

CONCLUSION

This study evaluated the effects of different coating treatments on the shelf life of apple fruit (cv. Golden Delicious) and identified the most effective coating for maintaining fruit quality during storage. The results revealed that during the 45-day storage period, T7 (sunflower oil) showed the best performance, with superior stability in biochemical attributes, along with the lowest weight loss and minimal decay loss. This was followed by T2 (aloe vera gel), which also maintained relatively stable chemical properties and exhibited reduced weight loss and decay. In contrast, the highest biochemical changes, weight loss, and decay loss were recorded in T3 (polyethylene plastic), followed by T6 (3% calcium chloride).

In summary, sunflower oil and aloe vera gel coatings were most effective in preserving apple fruit quality during the 45-day storage period. Based on these results, it is suggested that these coatings be utilized—considering their availability and economic feasibility—to maintain apple quality during storage. Furthermore, future studies are suggested to evaluate the effectiveness of these treatments on other apple cultivars under varying storage conditions.

Authors Contributions

- Rahmat Gul Hassanzai conceptualized and supervised the study.
- Mohammadullah Amin analyzed data.
- Aimal Shabir investigated and wrote the manuscript with input from all authors.
- All authors reviewed and approved the final version.

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