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EFFECT OF PACKAGING MATERIAL AND DARK STORAGE ON THE POSTHARVEST QUALITY AND SHELF LIFE OF NAVEL ORANGES *(Citrus sinensis L., Osbeck)*

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ABSTRACT

Despite having a stiff peel, oranges suffer from many internal physiological changes and pathological damage during the postharvest stage. Oranges have a limited postharvest shelf life at ambient conditions. Storage conditions and Packaging materials are crucial factors in extending shelf life and maintaining fruit quality. In the current study, Washington Navel oranges were employed to assess the storage of fruit in negative modified atmosphere conditions with lower O_2 and higher CO_2 created by different methods of packing such as perforated low-density polyethylene (LDPE), perforated polyethylene low density high molecular weight (LDHM) and perforated cardboard boxes (CB) and control fruits with no packing (NP) on fruit properties. All treatments were split into two sections that were stored in complete darkness and those that were stored under conditions of light at 23°C and 85% relative humidity for 20 days. The treatments were arranged in a completely randomized design (CRD) under factorial arrangement, and the whole experiment was replicated three times. Storage properties were assessed, and CD+LDHM treatment produced the best in maintaining weight loss (1.30%) and the least in fruit firmness change (41.36 N), TSS (11.36 Brix), total acidity (0.98%), and vitamin C (25.19 mg/100ml). It was followed closely by CD+LDPE treatment. On the other hand, the unpacked fruit had the highest weight loss and chemical or physical property changes, either under complete darkness or light conditions. The results indicated that This study demonstrated that modified atmosphere using perforated LDPE and LDMH packaging significantly improved the postharvest quality, extended the shelf life of Navel oranges, and reduced deterioration compared to carton boxes or unpackaged as a control.

Keywords: orange, postharvest, packaging, plastic materials, darkness, storage, shelf life, quality, enzymes

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INTRODUCTION

Citrus crops experience a substantial postharvest loss ratio ranging from 30 to 50% of the total production (Strano *et al*., 2022). In hot climates such as Saudi Arabia, a valuable loss ratio estimated at 28% in orange was reported (Alshabanat *et al*., 2021). Navel orange (*Citrus sinensis* L*., Osbeck*) is an important citrus crop. It has delicious and healthy fruits. On the other hand, fruits are highly perishable due to water loss and biochemical changes such as color and weight loss (Wan *et al*., 2020). Moreover, these changes include essential postharvest quality properties such as total soluble solids, acidity, ascorbic acid, phenols, and enzymatic activity (Xiong *et al*., 2025). Navel orange also suffers from significant losses resulting from postharvest pathogens (Du *et al*., 2021).

The light effect on some horticulture crops during the postharvest period could be positive such as citrus (*Citrus sinensis* L.) (Huang *et al*., 2023), grapes (*Vitis vinifera* L.) (Kong *et al*., 2024), and bilberry a non-climacteric (*Vaccinium myrtillus* L.), fruit (Samkumar, 2021). On the contrary, some crops should be stored under complete darkness to avoid quality deterioration, like broccoli (*Brassica oleracea var italica*) (Olarte *et al*., 2009), asparagus (*Asparagus officinalis L.*) (Sanz *et al*., 2009), and leek (*Allium ampeloprasum var porrum*) (Ayala *et al*., 2009). By controlling storage environmental factors such as humidity, temperature, and gas composition, the shelf life of horticulture crops can be extended. Light is a crucial factor that affects all growth and development along the stages of the plant life cycle (Botton *et al*., 2008). It strongly affects the quality of packed or unpacked fresh produce during the postharvest stage (Büchert *et al*., 2011). One of the most important types of evidence of fruit maturity is soluble solids increase and decline in titratable acidity (Sharabiani *et al*., 2020). These changes are directly proportional to light penetration in fruit tissues (Jia *et al*., 2016).

Most of the postharvest quality-maintaining methods are highly costly. The most common are cold storage, wax coating and fungicides. Moreover, using controlled atmosphere, anti-transpirant substances, and irradiation are also efficient (Rokaya *et al*., 2016). One of the greatest challenges is to find affordable alternatives. Modified atmospheric packaging (Modified atmospheric packaging (MAP) is an inexpensive and economical tool. Numerous polyethylene materials, such as low-density polyethylene (LDPE) and high-density molecular polyethylene (LDMH) can provide (MAP) conditions. A long chain of ethylene monomers is synthetically forming the polyethylene polymer. It is a common material for fruit and vegetable packaging (Kassim and Workneh, 2020). because it is a low-cost and simple material (Rodov *et al*., 2022). Using plastic films has been more important after being proven as an efficient material throughout all the steps of the supply chain, starting from harvesting, including storage and transportation until marketing (Mukhim *et al*., 2023). Micro-perforated LDPE film effectively prevents water condensation and adjusts the ratio of gases around the fruits, especially oxygen (O_2) and carbon dioxide (CO_2), as well as ethylene and nitrogen. It manipulates CO_2 and O_2 inside the package, resulting in balancing fruit respiration rate (Sonawane *et al*., 2022). High O_2 or low CO_2 ratios minimize respiration rate, slow ethylene production, and retarding ripening biochemical reactions in fruits, resulting in longer fruit shelf life (Poudel *et al*., 2022). It also declined in polyphenol oxidase enzyme activity that causes browning in fruit and vegetables (Buthelezi and Mafeo, 2024). Micro-perforated LDHM was used to extend the shelf life of Assam lemon fruits, which retained better green color (Mukhim *et al*., 2023). Although LDPE materials have been investigated in several studies, and their effects on some quality parameters, such as weight loss and firmness, are well known (Mukhim *et al*., 2023; Rasouli, 2025) but their effect on other biochemical traits needs further investigation. Moreover, LDHM Film has received very limited attention in fruit postharvest packaging until now, and its effectiveness in preserving fruit quality, especially oranges under ambient conditions, needs more studies to explore it.

This study aims to examine the effect of LDPE and LDHM and regular cardboard boxes on maintaining postharvest quality of navel orange under ambient conditions. Moreover, The effect of complete darkness storage conditions, either alone or in combination with the packaging materials, on the postharvest quality of oranges. Furthermore, finding out the effectiveness of these treatments as a practical alternative to cold storage.

MATERIALS AND METHODS

This study was carried out on Washington Navel orange fruits from a commercial orchard in Najran, Saudi Arabia. Healthy and uniform fruits without any disease's visual symptoms or mechanical damage were harvested at the maturity stage. Immediately after harvest, fruits were transported to the postharvest technology laboratory in the Agriculture Department, Environmental Science Faculty, King Abdulaziz University in Jeddah. All fruits were washed in distilled water for 1 min and dried on sterile filter paper. There were two factors in the study: four packaging types (no package, LDPE, LDHM, and cardboard) and two light conditions (light and darkness). The treatments were arranged in a completely randomized design (CRD) under factorial arrangement, and the whole treatments were replicated three times.

Treatment details: Three types of packaging materials used in this study: Low-density polyethylene (LDPE) 200-gauge (0.91 g/cm^3 density and 0.05 mm thickness), Low density high molecular weight (LDHM)100 gauge (0.94 g/cm^3 density and 0.025 mm thickness), and perforated cardboard (CB) (0.7 g/cm^3 density and 0.3 mm thickness). This study also included two light conditions. The light treatments (L) consist of a cycle of 12 hours of artificial light of a T8 LED fluorescent daylight tube (6000K) at approximately 1000 lux, followed by 12 hours of darkness. The complete darkness (CD) involved storing fruit in light-proof chambers without any light exposure throughout the storage period.

Each treatment contained three replicates of 30 fruits each. The fruits were randomly assigned to the treatment groups to minimize experimental bias and ensure uniformity across replicates. All fruits were stored under ambient conditions (23 ±1°C and 85-90% RH). Samples were taken at 4-day intervals for the following measurements.

Weight loss percentage (WL%): The weight loss percentage (WL%) was calculated according to the formula proposed by Mukhim *et al*. (2023) as under:

$$\text{Weight loss percentage (WL\%)} = \frac{\text{Initial weight} - \text{Final weight}}{\text{Initial weight}} \times 100$$

Fruit Peel lightness (L*) measurement: Peel lightness (L*.) was estimated by using a model colorimeter (color reader CR-410, Konica Minolta Inc., Japan), as described by McGuire (1992).

Fruit Peel Hue angle (h°) measurement: Peel Hue angle (h°) was estimated by using a model calorimeter (color reader CR-410, Konica Minolta Inc., Japan) (h° = Arctan (b*/a*) according to Habibi *et al*. (2021).

Fruit firmness (N): Fruit firmness was measured in peel using a pressure tester (Digital basic force gage (model BFG 50 N, Mecmesin, Sterling, Virginia, USA) with an appropriate plunger (11 mm) according to Valero *et al*. (2013).

Total soluble solids (TSS), Titratable acidity (TA), and Ascorbic acid measurements: TSS was estimated using a digital refractometer (Pocket Refractometer PAL 3, ATAGO, Japan) and expressed as a percentage. TA, as citric acid, was determined in juice samples and then calculated as a percentage. Ascorbic acid was determined with a 2% oxalic acid solution using the AOAC-recommended substrate of 2,6-dichlorophenolindophenol and expressed in mg/100 ml. All three traits were determined according to AOAC (2016).

Total phenol determination (TPC)

Preparation of the methanol extract: Two grams of peel were extracted with 20 mL of methanol (80%) by shaking at150 rpm for 24h and then filtered using filter paper No.1. The filtrate was designated as the ethanol extract. Estimation of total phenols.

The concentration of TPC was measured in fruit methanolic extract as described by Hoff and Singleton (1977) by adding 100 mL of Folin Ciocalteu reagent and 850 mL of methanol to 50mL of the methanol extract. The mixture was left at an ambient temperature for 5 minutes. Then, 500 mL of 20% sodium carbonate was added, and the mixture was incubated for 30 min. Absorbance at 750 nm wavelength was used for the measurement of the samples. The calibration curve of the absorbance of known concentrations of gallic acid was used to quantify total phenol concentration and was expressed in kg /1FW gallic acid equivalent.

Assessment of enzyme activities: Crude extract was prepared by homogenizing 1 g of peel taken from 10 fruit from each replicate in 20 mM Tris–HCl buffer (PH =7.2) and then centrifuged at 4 ºC for 10 min at 10,000 rpm. Enzyme activities were assessed in the supernatant as follows.

Polyphenoloxidase (PPO) enzyme: PPO (EC 1.14.18.1) was determined following the protocol of Jiang *et al*., (2002). A total of 0.2mL extract was mixed rapidly with 2.8 mL of 20mM catechol solution prepared in 0.01M sodium phosphate buffer (pH 6.8). At 400nm, the increase in absorbance was detected for 3min. One unit of enzyme activity was defined as the amount of the enzyme causing a change of 0.1 in absorbance per minute.

Peroxidase (POD) enzyme: POD (EC 1.11.1.7) was quantified as described by Miranda *et al*., (1995) in 1ml reaction mixture [0.008mL of 0.97M H_2O_2, 0.08mLof 0.5M guaiacol,0.2M sodium acetate buffer (pH 5.5), and the least amount of enzyme preparation]. At 470 nm. The change in absorbance over 1 minute due to guaiacol oxidation was measured to assess enzyme activity. One unit of enzyme activity was defined as the number of enzymes that increased the OD by 1.0 per 1 min under standard assay conditions.

Statistical analysis: The collected data were statistically analyzed by using two-way analysis of variance (ANOVA) with the statistical package software SAS (SAS Institute Inc., 2000, Cary, NC, USA). Means were compared using the F-test, and the least significant differences between treatments were determined using the least significant differences (LSD) at a significant level of p≤ 5%.

RESULTS

Weight loss: A significant interaction effect between packaging treatments and storage duration was observed on the weight loss percentage of Navel orange under ambient conditions (Table 1). By day 8, LDHM/CD, LDPE/CD, and CAB/CD maintained much lower weight loss percentage, ranging from 0.88 to 1.17% compared to the control (2.17%). Throughout the storage period, all packaging-darkness treatments continued to record the lowest values (1.10–1.23%) compared to the control and NP/CD (3.47-3.64). On the 20th day, the lowest percentage (1.30%) was recorded for LDPE/CD and LDHM/CD treatments, whereas the highest value (5.46%) was observed in the control fruit. This confirms that packaging combined with darkness was the most effective in reducing weight loss throughout storage.

Fruit lightning (L*): A significant interaction effect between packaging treatments and storage duration was detected for L* values (fruit lightning) of Navel orange under ambient conditions (Table 2). After 4 days, LDHM/CD and CAB/CD recorded the highest L* values (62.80 and 62.32, respectively), while NP/CD had the lowest value (60.03). As the storage progressed to 12 and 16 days, the packaging – darkness treatments such as LDHM/CD retained significantly higher values (60.13 and 59.27) compared with control fruits (55.82–53.22). On the last sampling date, NP/CD-treated fruits had the lowest L* value (49.89) with no significant differences with control fruits (50.52). On the contrary, the highest L* value (57.47) was noticed in the fruit subjected to LDHM/CD and LDPE/CD (55.37), suggesting better color preservation under plastic packaging and complete darkness.

Fruit hue angle (hº): Packaging materials and storage duration significantly affected the hue angle (hº)of Navel orange under ambient conditions (Table 3). Gradual decrease in the values of the hue angle (hº) was noticed along the storage period showing that fruit colors turn from green to orange. On the 4th day, CAB/L and LDPE/L treatments exhibited the highest values (70.58 and 69.65, respectively), while LDHM/CD and CAB/CD showed lower values (67.57 and 67.94). After 12 storage days, CAB/L (67.32) and NP/CD (67.10) still retained higher hue compared with LDHM/CD (64.74) and CAB/CD (64.57). On the 20th day, the lowest value (61.29) was founded in the control and CAB/CD. The highest values were shown by LDHM/CD (62,79) and CAB/L (62,44).

Firmness: Packaging materials and storage duration exhibited a significant effect on Navel orange firmness under ambient conditions (Table 4). On day 8, fruit stored in LDHM/CD, LDPE/CD, and CAB/CD maintained higher firmness (54.70 to 55.28N) compared with the control (50.28N). After 12 days, firmness remains significantly higher in LDHM/CD (53.99N), while the control dropped to 48.06N. At the end of the storage period, LDHM/CD treatment significantly preserved fruit firmness (53.10N), followed by LDPE/CD (51.90N), indicating the protective effect of plastic packaging with darkness. The lowest value (41.36N) was observed in untreated fruits and NP/CD (45.61N).

Total soluble solids (TSS): Total soluble solids (TSS) content of Navel orange significantly affected by the interaction between packaging materials and storage duration under ambient conditions (Table 5). As storage progressed, TSS values gradually increased in all treatments. On the 12th day, in control and CAB/L showed the highest TSS values (12.40 and 12.22^{o}Brix), respectively. On the contrary, the lowest values were exhibited by LDPE/CD (11.62^{o}Brix) and LDHM/CD (11.75^{o}Brix). At the end of the experiment, TSS remained the highest in control (12.65^{o}Brix), followed by CAB/L(12.37^{o}Brix), whereas the lowest values were detected in LDHM/CD and LDHM/L (11.77and 11.80^{o}Brix), respectively as evidence of the efficiency of LDHM packaging under light or darkness in maintaining lower TSS levels resulting in slower ripening compared with the control.

Titratable acidity (TA%): Packaging materials and storage duration significantly affected the titratable acidity (TA%) of Navel orange under ambient conditions (Table 6). On day 8, The highest TA values were recorded in LDPE (0.94%) and LDHM (0.96%) packaging in combination with light or darkness, while the lowest was found in the control (0.77%). On the 12th day, the TA level in LDHM/CD (%) and LDPE/CD treatments (0.87 and 0.85%) respectively were relatively higher compared with control (0.68). After 20 days, Control fruits showed the lowest TA level (0.53%) on the other hand, the highest level were recorded in LDHM/CD (0.77%) and LDPE (0.75%). These results indicate that LDHM/CD packaging slowed down the fruit ripening compared with the control.

Ripening index (TSS/TA): There was a significant interaction effect between packaging materials and storage period was observed on the ripening index (TSS/TA) of Navel orange under ambient conditions (Table 8). After 8 days, control (15.78) and CAB/L (14.76) exhibited a higher ripening index compared to LDPE/CD (12.39) and LDPE/L (12.46). On The16th day, the index peaked at 21.16 in control, followed by CAB/L (17.66), while LDPE/L (15.87) and LDHM/CD (14.56) slowed down ripening. On the last day, the ripening index reached the maximum in control (24.45), followed by CAB/L (19.11), while the lowest values persisted in LDPE/L (17.03) and LDHM/CD (15.40), showing that polyethylene packaging films either under darkness or light slowed down ripening, while control and cardboard packaging under light accelerated the ripening process.

Ascorbic acid: Ascorbic acid content of Navel orange significantly affected by the interaction between packaging treatments and storage duration under ambient conditions (Table 8). Ascorbic acid gradually declined over time, but the rate of reduction varied with treatments. After 4 days, LDHM/CD and LDPE/CD (25.19 and 24.81 mg/ 100ml) respectively showed the highest ascorbic acid content, on the contrary, control recorded the lowest value (23.70 mg/100 ml). control fruits showed a sharper reduction (21.85 mg/100ml) after 8 days, whereas LDHM/CD (24.07 mg/100ml) and LDPE/CD (23.33 mg/100 ml) significantly maintained higher content of ascorbic acid. At the last sampling date, control showed the minimum value (18.52 mg/100 ml), while LDHM/CD (22.59 mg/100 ml) and LDPE/CD (21.85 mg/100 ml) retained the highest levels. This showing that LDHM/CD and LDPE/CD packaging in combination with darkness was most effective in delaying ascorbic acid loss, whereas control fruits experienced the fastest depletion.

Total Phenols (TPC): The combination of packaging treatments and storage duration significantly influenced total phenolic content (TPC) of Navel orange under ambient conditions (Table 9). A general decline was observed with advancing storage. By reaching day 4, the highest TPC were preserved in LDHM/CD (1.66 mg/100ml) and LDPE/CD (1.65 mg/100ml) while the control showed a sharper decrease (1.42 mg/100ml). A similar trend persisted throughout the storage period. On the 20th day, the lowest phenolic content (1.12 mg/100ml) was founded in control, while the highest content was observed in LDHM/CD and LDPE/CD (1.39 and 1.38 mg/100ml) respectively. LDHM and LDPE polyethylene packages under dark storage conditions significantly preserved the phenolic compounds compared with all other treatments, indicating their effectiveness in slowing oxidative degradation.

Enzyme activity: Polyphenoloxidase (PPO) activity of Navel orange was markedly affected by packaging treatments and storage duration under ambient conditions (Table 10). A sharp decline occurred on day 4 since the lowest activity was observed in the control (11.87

Table 1: Effect of packaging materials and Light/dark storage conditions on weight loss (%) of Navel orange fruits under ambient conditions

Shelf life (days)	Control	No package + complete darkness (NP/CD)	Low density polyethylene + 12hr light (LDPE/L)	low density high molecular weight + 12hr light (LDHM/L)	Cardboard boxes + 12hr light (CAB/L)	Low density polyethylene + complete darkness (LDPE/CD)	Low density high molecular weight + complete darkness (LDHM/CD)	Cardboard boxes + complete darkness (CAB/CD)
0	0.00 ^{p}	0.00 ^{p}	0.00 ^{p}	0.00 ^{p}	0.00 ^{p}	0.00 ^{p}	0.00 ^{p}	0.00 ^{p}
4	2.21 $^{f-j}$	2.07 $^{g-l}$	1.23 $^{m-o}$	1.47 $^{j-o}$	2.27 $^{f-i}$	0.77 ^{op}	0.97 ^{no}	0.87 ^{o}
8	2.76 $^{d-g}$	2.47 $^{e-h}$	1.50 $^{i-o}$	1.47 $^{j-o}$	2.40 $^{e-h}$	0.88 ^{o}	1.07 $^{m-o}$	1.17 $^{m-o}$
12	3.47 ^{cd}	2.67 $^{e-g}$	1.80 $^{h-m}$	1.53 $^{i-o}$	2.60 $^{e-g}$	1.13 $^{m-o}$	1.10 $^{m-o}$	1.23 $^{m-o}$
16	3.64 ^{bc}	2.90 $^{c-f}$	2.10 $^{g-k}$	1.73 $^{h-n}$	2.90 $^{c-f}$	1.20 $^{m-o}$	1.23 $^{m-o}$	1.43 $^{k-o}$
20	5.46 ^{a}	4.38 ^{b}	2.17 $^{f-k}$	1.80 $^{h-m}$	3.10 $^{c-e}$	1.30 $^{l-o}$	1.30 $^{l-o}$	1.53 $^{i-o}$
LSD value		A = 0.28			B= 0.32		A*B = 0.78	

Means with the same letters (small case letters for interactions and capital case letters for individual effects) are not significantly different at $P \leq 0.05\%$ according to LSD. test.
Here A= Packaging material; B= Storage duration

Table 2: Effect of packaging materials and Light/dark storage conditions on fruit lightening (L*) of Navel orange under ambient conditions

Shelf life (days)	Control	No package + complete darkness (NP/CD)	Low density polyethylene + 12hr light (LDPE/L)	low density high molecular weight + 12hr light (LDHM/L)	Cardboard boxes + 12hr light (CAB/L)	Low density polyethylene + complete darkness (LDPE/CD)	Low density high molecular weight + complete darkness (LDHM/CD)	Cardboard boxes+complete darkness (CAB/CD)
0	64.94 ^{a}	64.94 ^{a}	64.94 ^{a}	64.94 ^{a}	64.94 ^{a}	64.94 ^{a}	64.94 ^{a}	64.94 ^{a}
4	61.10 $^{a-g}$	60.03 $^{b-h}$	61.22 $^{a-}$g	61.72 $^{a-d}$	61.42 $^{a-f}$	61.63 $^{a-e}$	62.80 ^{ab}	62.32 $^{a-c}$
8	57.70 $^{f-m}$	56.96 $^{h-n}$	58.35 $^{d-l}$	58.67 $^{c-k}$	57.77 $^{e-m}$	58.79 $^{c-j}$	60.97 $^{b-}$g	60.14 $^{b-h}$
12	55.82 $^{i-q}$	54.83 $^{k-}$r	56.75 $^{h-}$o	57.67 $^{f-m}$	56.47 $^{h-}$p	57.69 $^{f-m}$	60.13 $^{b-h}$	59.07 $^{b-j}$
16	53.22 $^{n-s}$	51.99 q^{-}s	54.82 $^{k-}$r	56.60 $^{h-}$p	54.40 $^{m-}$r	55.59 $^{i-}$r	59.27 $^{b-i}$	57.40 g^{-m}
20	50.52 s	49.89 s	52.85 p^{-}s	54.70^{nl-}r	51.94^{n}rs	53.06^{n}o^{-}s	57.47^{n}g^{-m}	55.37^{nj-}r
LSD value		A = 1.37		B = 1.58			A*B = 3.88	

Means with the same letters (small case letters for interactions and capital case letters for individual effects) are not significantly different at $P \leq 0.05\%$ according to LSD. test.
Here A= Packaging material; B= Storage duration

Table 3: Effect of packaging materials and Light/dark storage conditions on Fruit hue angle (h°) of Navel orange fruits under ambient conditions

Shelf life (days)	Control	No package + complete darkness (NP/CD)	Low density polyethylene + 12hr light (LDPE/L)	low density high molecular weight + 12hr light (LDHM/L)	Cardboard boxes + 12hr light (CAB/L)	Low density polyethylene + complete darkness (LDPE/CD)	Low density high molecular weight + complete darkness (LDHM/CD)	Cardboard boxes + complete darkness (CAB/CD)
0	72.47^{a}	72.47^{a}	72.47^{a}	72.47^{a}	72.47^{a}	72.47^{a}	72.47^{a}	72.47^{a}
4	69.60^{bc}	69.60^{bc}	68.80^{c-f}	69.65^{bc}	70.58^{b}	67.57^{d-i}	66.78^{g-j}	67.94^{c-h}
8	68.22^{c-g}	68.96^{b-e}	67.91^{c-h}	68.31^{c-g}	69.17^{b-d}	66.60^{g-j}	65.67^{j-l}	66.37^{h-k}
12	66.28^{h-l}	67.10^{f-j}	66.01^{i-l}	66.39^{h-k}	67.32^{e-j}	64.74^{k-m}	63.79^{m-o}	64.57^{l-n}
16	62.93^{n-p}	63.29^{m-o}	62.88^{n-p}	63.02^{m-p}	63.41^{m-o}	62.62^{op}	62.43^{op}	62.73^{op}
20	61.29^{p}	62.38^{op}	61.20^{p}	62.79^{n-p}	62.44^{p}	61.28^{p}	61.27^{p}	61.29^{p}
LSD value		A = 0.63		B = 0.72			A*B = 1.77	

Means with the same letters (small case letters for interactions and capital case letters for individual effects) are not significantly different at P≤ 0.05% according to LSD. test.
Here A= Packaging material; B= Storage duration

Table 4: Effect of packaging materials and Light/dark storage conditions on Fruit Firmness (N) of Navel orange fruits under ambient conditions

Shelf life (days)	Control	No package + complete darkness (NP/CD)	Low density polyethylene + 12hr light (LDPE/L)	low density high molecular weight + 12hr light (LDHM/L)	Cardboard boxes + 12hr light (CAB/L)	Low density polyethylene + complete darkness (LDPE/CD)	Low density high molecular weight + complete darkness (LDHM/CD)	Cardboard boxes + complete darkness (CAB/CD)
0	55.93^{a}	55.93^{a}	55.93^{a}	55.93^{a}	55.93^{a}	55.93^{a}	55.93^{a}	55.93^{a}
4	53.72^{a-h}	54.50^{a-f}	54.94^{a-d}	55.17^{a-c}	54.83^{a-e}	55.34^{a-c}	55.65^{ab}	54.97^{a-d}
8	50.82^{f-m}	52.96^{a-j}	53.63^{a-i}	54.04^{a-h}	53.46^{a-i}	54.70^{a-e}	55.28^{a-c}	53.95^{a-h}
12	48.06^{l-n}	51.11^{e-m}	52.12^{b-k}	52.66^{a-j}	51.70^{c-l}	53.99^{a-h}	54.79^{a-e}	52.88^{a-j}
16	44.96^{no}	48.41^{k-n}	50.60^{g-m}	51.26^{d-m}	49.87^{i-m}	53.23^{a-j}	54.26^{a-g}	51.74^{c-l}
20	41.36^{o}	45.61^{n}	48.74^{k-n}	49.62^{j-m}	47.89^{mn}	51.90^{b-k}	53.10^{a-j}	50.33^{h-m}
LSD value		A = 1.34		B = 1.55			A*B = 3.79	

Means with the same letters (small case letters for interactions and capital case letters for individual effects) are not significantly different at P ≤ 0.05% according to LSD. test.
Here A= Packaging material; B= Storage duration

Table 5: Effect of packaging materials and Light/dark storage conditions on total soluble solids (°Brix) of Navel orange fruits under ambient conditions

Shelf life (days)	Control	No package +complete darkness (NP/CD)	Low density polyethylene + 12hr light (LDPE/L)	low density high molecular weight + 12hr light (LDHM/L)	Cardboard boxes + 12hr light (CAB/L)	Low density polyethylene + complete darkness (LDPE/CD)	Low density high molecular weight + complete darkness (LDHM/CD)	Cardboard boxes + complete darkness (CAB/CD)
0	11.04 t	11.04 t	11.04 ^{t}	11.04 ^{t}	11.04 ^{t}	11.04 t	11.04 t	11.04 ^{t}
4	11.86 $^{h-m}$	11.54 ^{n}-s	11.47 $^{p-s}$	11.45 q-s	11.74 ^{i}-r	11.42 rs	11.36 s	11.48 o-s
8	12.06 $^{d-h}$	11.91 $^{f-k}$	11.64 j-s	11.56 $^{m-s}$	11.90 $^{f-k}$	11.53 ^{n}-s	11.42 rs	11.71 $^{i-r}$
12	12.40 $^{a-c}$	12.07 $^{c-h}$	11.75 $^{h-q}$	11.62 $^{k-s}$	12.22 $^{b-f}$	11.67 ^{j}-s	11.57 ^{l}-s	11.89 $^{g-l}$
16	12.50 ^{ab}	12.32 $^{b-e}$	11.83 $^{h-n}$	11.73 $^{i-r}$	12.37 $^{a-d}$	11.80 ^{h}-o	11.69 ^{j}-s	12.03 $^{e-i}$
20	12.65 ^{a}	12.43 ^{ab}	11.92 $^{f-k}$	11.80 $^{h-p}$	12.53 ^{ab}	11.96 $^{f-j}$	11.77 ^{h}-q	12.21 $^{b-g}$
LSD value			A = 0.11		B = 0.13		A*B = 0.32	

Means with the same letters (small case letters for interactions and capital case letters for individual effects) are not significantly different at $P \leq 0.05\%$ according to LSD. test.
Here A= Packaging material; B= Storage duration

Table 6: Effect of packaging materials and Light/dark storage conditions on titratable acidity (TA%) of Navel orange fruits under ambient conditions

Shelf life (days)	Control	No package + complete darkness (NP/CD)	Low density polyethylene + 12hr light (LDPE/L)	low density high molecular weight + 12hr light (LDHM/L)	Cardboar d boxes + 12hr light (CAB/L)	Low density polyethylene + complete darkness (LDPE/CD)	Low density high molecular weight + complete darkness (LDHM/CD)	Cardboard boxes + complete darkness (CAB/CD)
0	1.00 ^{a}	1.00 ^{a}	1.00 ^{a}	1.00 ^{a}	1.00 ^{a}	1.00 ^{a}	1.00 ^{a}	1.00 ^{a}
4	0.83 $^{c\_i}$	0.87 $^{a\_g}$	0.98 ^{ab}	0.98 ^{ab}	0.90 $^{a\_f}$	0.98 ^{ab}	0.98 ^{ab}	0.92 $^{a\_e}$
8	0.77 $^{f\_k}$	0.83 $^{c\_i}$	0.94 $^{a\_d}$	0.96 $^{a\_c}$	0.81 $^{d\_j}$	0.94 $^{a\_d}$	0.96 $^{a\_c}$	0.83 $^{c\_i}$
12	0.68 $^{j\_l}$	0.75 $^{g\_k}$	0.79 $^{e\_k}$	0.83 $^{c\_i}$	0.75 $^{g\_k}$	0.85 $^{b\_h}$	0.87 $^{a\_g}$	0.79 $^{e\_k}$
16	0.60 ^{lm}	0.73 $^{h\_l}$	0.75 $^{g\_k}$	0.79 $^{e\_k}$	0.70 $^{i\_l}$	0.79 $^{e\_k}$	0.81 $^{d\_j}$	0.73 $^{h\_l}$
20	0.53 ^{m}	0.68 $^{j\_l}$	0.70 $^{i\_l}$	0.75 $^{g\_k}$	0.66 $^{k\_m}$	0.73 $^{h\_l}$	0.77 $^{f\_k}$	0.70 $^{i\_l}$
LSD value		A = 0.051		B = 0.059			A*B = 0.15	

Means with the same letters (small case letters for interactions and capital case letters for individual effects) are not significantly different at $P \leq 0.05\%$ according to LSD. test.
Here A= Packaging material; B= Storage duration

Table 7: Effect of packaging materials and Light/dark storage conditions on ripening index (TSS/TA) of Navel orange fruits under ambient conditions

Shelf life (days)	Control	No package + complete darkness (NP/CD)	Low density polyethylene + 12hr light (LDPE/L)	low density high molecular weight + 12hr light (LDHM/L)	Cardboard boxes + 12hr light (CAB/L)	Low density polyethylene+ complete darkness (LDPE/CD)	Low density high molecular weight + complete darkness (LDHM/CD)	Cardboard boxes + complete darkness (CAB/CD)
0	11.18 ^{r}	11.18 ^{r}	11.18 ^{r}	11.18 ^{r}	11.18 ^{r}	11.18 ^{r}	11.18 ^{r}	11.18 ^{r}
4	14.31 $^{i-o}$	13.21 $^{l-r}$	11.70 ^{qr}	11.68 ^{qr}	13.14 $^{l-r}$	11.78 ^{qr}	11.60 ^{r}	12.53 $^{m-r}$
8	15.78 $^{e-k}$	14.37 $^{i-o}$	12.46 $^{m-r}$	12.04 $^{o-r}$	14.76 $^{g-m}$	12.39 $^{n-r}$	11.90 $^{p-r}$	14.13 $^{j-p}$
12	18.29 ^{cd}	16.26 $^{d-k}$	14.91 $^{g-l}$	14.03 $^{k-q}$	16.44 $^{d-j}$	14.47 $^{h-n}$	13.34 $^{l-r}$	15.09 $^{f-l}$
16	21.16 ^{b}	17.01 $^{c-g}$	15.87 $^{e-k}$	14.88 $^{g-l}$	17.66 $^{c-e}$	14.97 $^{c-e}$	14.56 $^{h-n}$	16.72 $^{d-h}$
20	24.25 ^{a}	18.34 ^{cd}	17.03 $^{c-g}$	15.83 $^{e-k}$	19.11 ^{bc}	16.52 $^{d-i}$	15.40 $^{e-l}$	17.34 $^{c-f}$
LSD value			A = 0.83			B = 0.96	A*B = 2.35	

Means with the same letters (small case letters for interactions and capital case letters for individual effects) are not significantly different at P≤ 0.05% according to LSD. test.
Here A= Packaging material; B= Storage duration

Table 8: Effect of packaging materials and Light/dark storage conditions on Ascorbic acid (mg/100ml) of Navel orange fruits under ambient conditions

Shelf life (days)	Control	No package +complete darkness (NP/CD)	Low density polyethylene + 12hr light (LDPE/L)	low density high molecular weight + 12hr light (LDHM/L)	Cardboard boxes +12hr light (CAB/L)	Low density polyethylene +complete darkness (LDPE/CD)	Low density high molecular weight+ complete darkness (LDHM/CD)	Cardboard boxes + complete darkness (CAB/CD)
0	25.93 ^{a}	25.93 ^{a}	25.93 ^{a}	25.93 ^{a}	25.93 ^{a}	25.93 ^{a}	25.93 ^{a}	25.93 ^{a}
4	23.70 $^{c-f}$	24.07 $^{b-e}$	24.44 $^{b-d}$	24.44 $^{b-d}$	24.07 $^{b-e}$	24.81 $^{a-c}$	25.19 ^{ab}	24.07 $^{b-e}$
8	21.85 $^{h-k}$	21.48 $^{i-l}$	22.96 $^{e-h}$	23.70 $^{c-f}$	21.85 $^{h-k}$	23.33 $^{d-g}$	24.07 $^{b-e}$	23.70 $^{c-f}$
12	20.37 $^{l-n}$	20.74 $^{k-n}$	22.59 $^{f-i}$	22.96 $^{e-h}$	21.85 $^{h-k}$	22.22 $^{g-j}$	23.33 $^{d-g}$	22.22 $^{g-j}$
16	20.00 ^{mn}	20.74 $^{k-n}$	22.22 $^{g-j}$	22.96 $^{e-h}$	21.11 $^{j-m}$	21.85 $^{h-k}$	22.59 $^{f-i}$	22.22 $^{g-j}$
20	18.52 ^{o}	20.00 ^{mn}	21.11 $^{j-m}$	21.48 $^{i-l}$	19.63 ^{no}	21.48 $^{i-l}$	22.59 $^{f-i}$	21.85 $^{h-k}$
LSD value		A = 0.50		B = 0.58			A*B = 1.42	

Means with the same letters (small case letters for interactions and capital case letters for individual effects) are not significantly different at P ≤ 0.05% according to LSD. test.
Here A= Packaging material; B= Storage duration

Table 9: Effect of packaging materials and Light/dark storage conditions on total phenols (mg/100ml) of Navel orange fruits under ambient conditions

Shelf life (days)	Control	No package+ complete darkness (NP/CD)	Low density polyethylene+12 hr light (LDPE/L)	low density high molecular weight+12hr light (LDHM/L)	Cardboard boxes+12hr light (CAB/L)	Low density polyethylene + complete darkness (LDPE/CD)	Low density high molecular weight + complete darkness (LDHM/CD)	Cardboard boxes + complete darkness (CAB/CD)
0	1.68^{a}	1.68^{a}	1.68^{a}	1.68^{a}	1.68^{a}	1.68^{a}	1.68^{a}	1.68^{a}
4	1.42^{a-j}	1.48^{a-g}	1.55^{a-e}	1.57^{a-d}	1.47^{a-h}	1.65^{ab}	1.66^{ab}	1.62^{a-c}
8	1.29^{e-m}	1.35^{c-l}	1.42^{a-j}	1.44^{a-i}	1.34^{d-m}	1.52^{a-f}	1.53^{a-f}	1.49^{a-g}
12	1.08^{m}	1.14^{k-m}	1.21^{h-m}	1.23^{g-m}	1.13^{k-m}	1.31^{d-m}	1.32^{d-m}	1.27^{f-m}
16	1.12^{lm}	1.18^{i-m}	1.25^{g-m}	1.27^{f-m}	1.16^{j-m}	1.35^{c-m}	1.36^{c-l}	1.31^{d-m}
20	1.15^{k-m}	1.21^{h-m}	1.28^{f-m}	1.30^{e-m}	1.20^{i-m}	1.38^{c-l}	1.39^{b-k}	1.34^{c-m}
LSD value		A = 0.10		B = 0.11			A*B = 0.27	

Means with the same letters (small case letters for interactions and capital case letters for individual effects) are not significantly different at $P \leq 0.05\%$ according to LSD. test.
Here A= Packaging material; B= Storage duration

Table 10: Effect of packaging materials and Light/dark storage conditions on Polyphenoloxidase activity (Units/mg/sec) of Navel orange fruits under ambient conditions

Shelf life (days)	Control	No package + complete darkness (NP/CD)	Low density polyethylene+12hr light (LDPE/L)	low density high molecular weight + 12hr light (LDHM/L)	Cardboard boxes + 12hr light (CAB/L)	Low density polyethylene +complete darkness (LDPE/CD)	Low density high molecular weight+ complete darkness (LDHM/CD)	Cardboard boxes + complete darkness (CAB/CD)
0	36.39^{a}	36.39^{a}	36.39^{a}	36.39^{a}	36.39^{a}	36.39^{a}	36.39^{a}	36.39^{a}
4	11.87^{b}	12.35^{b}	12.93^{b}	13.10^{b}	12.26^{b}	13.77^{b}	13.86^{b}	13.48^{b}
8	10.78^{b}	11.26^{b}	11.84^{b}	12.01^{b}	11.17^{b}	12.70^{b}	12.78^{b}	12.39^{b}
12	8.99^{b}	9.47^{b}	10.05^{b}	10.22^{b}	9.38^{b}	10.90^{b}	10.98^{b}	10.60^{b}
16	9.32^{b}	9.80^{b}	10.38^{b}	10.55^{b}	9.71^{b}	11.21^{b}	11.31^{b}	10.93^{b}
20	9.60^{b}	10.08^{b}	10.66^{b}	10.82^{b}	9.98^{b}	11.50^{b}	11.59^{b}	11.20^{b}
LSD value		A = 4.73		B = 5.47			A*B = 13.40	

Means with the same letters (small case letters for interactions and capital case letters for individual effects) are not significantly different at $P \leq 0.05\%$ according to LSD. test.
Here A= Packaging material; B= Storage duration

Table 11: Effect of packaging materials and Light/dark storage conditions on peroxidase activity (Units/mg/sec) of Navel orange fruits under ambient conditions

Shelf life (days)	Control	No package + complete darkness (NP/CD)	Low density polyethylene + 12hr light (LDPE/L)	low density high molecular weight + 12hr light (LDHM/L)	Cardboard boxes + 12hr light (CAB/L)	Low density polyethylene + complete darkness (LDPE/CD)	Low density high molecular weight + complete darkness (LDHM/CD)	Cardboard boxes + complete darkness (CAB/CD)
0	42.22	42.22	42.22	42.22	42.22	42.22	42.22	42.22
4	64.44	54.44	48.33	46.39	52.50	45.28	44.72	51.39
8	66.67	60.83	52.50	50.28	59.17	50.28	48.33	56.39
12	65.28	58.06	51.67	48.06	55.00	48.06	45.28	53.33
16	63.06	54.44	49.17	45.83	52.78	45.56	43.89	51.67
20	56.94	51.39	47.22	43.61	49.17	39.72	42.50	50.28
LSD value		A = 12.08		B = 13.9			A*B = 34.15	

Means with the same letters (small case letters for interactions and capital case letters for individual effects) are not significantly different at $P \leq 0.05\%$ according to LSD. test.
Here A= Packaging material; B= Storage duration

Units/mg/sec). On the other hand, LDHM/CD exhibited the highest (13.86 Units/mg/sec). The same trend was detected after 12 days, the control recorded (8.99 Units/mg/sec) and the dark stored packaging films, particularly CAB/CD and LDHM/CD (11.67 and 10.98 Units/mg/sec) respectively, maintained higher activity. At the last two sampling dates (16 and 20) gradual stabilization was noticed, with values ranging between 9.32 and 11.59 Units/mg/sec, indicating enzymatic activity reduction compared to early storage. These findings exhibited that PPO activity decreased substantially across storage, with significantly higher residual activity retained in fruits stored in darkness with LDHM and LDPE polyethylene packages, suggesting that packaging combined with darkness helped to mitigate oxidative enzyme degradation.

Peroxidase (POD) activity of Navel orange was significantly affected by packaging treatments and storage duration under ambient conditions (Table 11). During the storage period, activity initially increased reaching peak values after 8 days, with the highest levels in control (66.67 Units/mg/sec), and slightly lower in NP/CD (60.83 Units/mg/sec), while fruits treated with LDPE/CD (50.28 nits/mg/sec), and LDHM/CD (48.33 Units/mg/sec) showed more moderate increase. Starting From day 12 POD activity gradually declined, with the lowest values founded in LDPE/CD and LDHM/CD (39.72 and 42.50 Units/mg/sec) respectively. On day 20, control remained relatively higher (56.94 nits/mg/sec). Fruits stored in LDHM and LDPE polyethylene packages in combination with darkness exhibited a moderate (POD) response compared to light-exposed or control fruits. Overall, dark packaging treatments helped to stabilize enzymatic activity and potentially reduced oxidative stress during storage.

DISCUSSION

Weight loss percentage significantly increased during the storage period. This is consistent with the typical behavior of citrus fruits when stored under ambient conditions (Emamifar *et al*., 2010; Ali *et al*., 2011; Mukhim *et al*., 2023). This increase is essentially due to moisture loss through stomatal opening that occurs during the evapotranspiration process. Respiration causes moisture loss as well, but to a lesser extent (Uddin *et al*., 2014; Lufu *et al*., 2019). Among the treatments, LDPE/CD and LDHM packaging exhibit the lowest weight loss, indicating the effectiveness of both low-permeability packaging and dark storage in minimizing moisture loss. These films create modified atmosphere conditions that slow down metabolism and reduce water evaporation (Kader, 2002). The LDPE and LDHM films have low gas and water permeability, resulting in maintaining high relative moisture around the fruits and reducing transpiration rates (Valero *et al*., 2007; Mahajan *et al*., 2008). Complete darkness was effective in reducing weight loss percentage since it avoids the local higher temperature on the fruit surface resulting from light exposure. It reduces fruit respiration by minimizing the light physiological stresses since light might stimulate stomatal opening, leading to more transpiration and therefore, higher weight loss than fruit stored in darkness (Pristijono *et al*., 2019).

Fruit firmness declined significantly during storage. Orange stored under ambient conditions has a high respiration rate, accelerates pectin and cell wall degradation, resulting in fruit softening and deterioration (Alhassan *et al*., 2024). Moreover, it increases moisture loss, results in macromolecule degradation, and therefore reduces fruit firmness (Kassebi and Korzenszky, 2024). LDPE and LDHM packaging with dark storage efficiently preserved fruit firmness compared to the other treatments. These films limit oxygen influx and water loss, subsequently lowering respiration rate and reducing substrate availability for microbial and enzymatic degradation (Alhassan *et al*., 2024). Dark storage provides cooler conditions that, by eliminating the heat associated with light exposure, complete darkness helps reduce the local temperatures and consequently decrease fruit respiration and water losses, resulting in firmness preservation.

The results showed that fruit subjected to CD/LDHM treatments had significantly the highest L* value and the lowest TSS content compared to untreated fruits. These findings are consistent with the previous studies of Jia *et al*. (2016). on grapes (Mukhim *et al*., 2015, 2023), on lemon (Yu *et al*., 2021), and on both grape and tomato. Abscisic acid (ABA) is essential in fruit coloring, softening, and sugar accumulation. There is a direct proportion between ABA content and fruit ripening traits (Jia *et al*., 2016). The ABA regulates carotenoid content in fruits (Yu *et al*., 2021). TSS content is determined by sugar biosynthesis, transport, and storage in fruits (Manoharan *et al*., 2017). Sugar accumulation decreases in fruits in darkness may affect the ABA content. Moreover, this reduction in ABA slows the carotenoid metabolism in fruits. Besides complete dark storage conditions, the LDHM treatments provide more darkness due to their opaque plastic nature. This highly reduces chlorophyll degradation, carotenoid biosynthesis, and TSS content in fruits. LDHM and LDPE low permeability preserve internal moisture and reduce sugars throughout dehydration. Similar findings by Han (2014) confirmed the ability of LDPE and similar films to reduce gas exchange and water loss, maintaining fruit quality during storage. Darkness reduces physiological processes such as respiration, transpiration, and moisture loss. These processes are related to TSS through sugar concentrations. Thus, limiting these processes in complete darkness helps to preserve more stable TSS levels in fruits (Toivonen and Brummell, 2008).

TA percentage decreases for all treatments at all storage dates. This may be resulting from the consumption of acids by fruit respiration throughout the tricarboxylic acid cycle (Dabargainya *et al*., 2022). Fruits treated with CD/LDHM showed a significantly higher titratable acidity TA content compared to the untreated fruits. In complete darkness, the local temperature around the fruits is relatively lower due to the absence of the heat accompanied by light (Pristijono *et al*., 2019). This is maybe attributed to the decreasing fruit respiration rate, which maintains higher acidity within fruits. Opaque LDHM packages contribute to maintaining more acidity in fruits through reducing light penetration, minimizing surrounding temperature, resulting in fruits' lower respiration rate. These results were in accordance with Bhat *et al*. (2004) and Kumar *et al*. (2023) on mandarin and Mukhim *et al*. (2015) on lemon.

Ascorbic acid, like other antioxidants, declines during postharvest storage, especially at ambient conditions. Several factors, including respiration, light exposure, oxidation, and enzymes, contribute to ascorbic acid loss (Lee and Kader, 2000). LDPE and LDHM packaging combined with dark storage effectively preserved ascorbic acid by acting as oxygen and moisture barriers, reducing respiration and slowing oxidative degradation (Han, 2014; Nath *et al*., 2012; Sozzi *et al*., 2009; Mukhim *et al*., 2023). Darkness was particularly important because light stimulates photo-oxidation of ascorbic acid and phenolic compounds (Toor and Savage, 2006), and citrus ascorbic acid is highly sensitive to light, especially at elevated temperatures and oxygen levels (Kader, 2002).

Phenolic compounds (TPC) are usually degraded into fresh fruits such as citrus during the postharvest storage. Phenolic degradation results from high respiration rate and enzymes activity, at ambient conditions. Polyphenoloxidase (PPO) causes fruit quality loss since it catalyzes the oxidation of phenolic compounds to quinones. Therefore, reducing PPO activity is a major goal of maintaining fruit quality. Peroxidase (POD) is another oxidative enzyme involved in response to mechanical damage, pathogen attack, oxidative stress, and environmental stress. Although POD has a protective role, its excessive activity can accelerate fruit deterioration and shorten its shelf life. (Toivonen and Brummell, 2008).

Using LDHM and LDPE packaging in combination with dark storage resulted in higher (TPC) content. These packaging materials are designed to limit oxygen and moisture permeability, thereby reducing phenolic oxidation. Since PPO is an oxygen-dependent enzyme. Thus, the modified atmosphere with low O_2 inhibits enzyme activity. POD activity has also reduced since it needs oxygen for enzyme function. When these films are combined with dark storage, a favorable modified atmosphere environment is created, which helps in slowing down degradation processes, including phenolic loss through reducing light exposure, oxygen availability, and moisture loss around the fruits (Han, 2014). Moreover, dark storage preserves phenolic compounds by reducing light-induced oxidative stress. It also limits the activation of oxidative enzymes such as PPO and POD. (Li *et al*., 2022). Light exposure has been shown to activate the PPO gene and stimulate the oxidative pathway (Tomás and Espin, 2001). Furthermore, reducing light exposure helps minimize respiration and oxidative reactions.

Conclusion: This study showed that modified atmosphere provided throughout using perforated LDPE and LDMH packaging significantly improved the postharvest quality, extended the shelf life of Navel oranges, compared to carton boxes or unpackaged as a control. The treated fruit significantly improved weight loss (1.30%), firmness (55.65 N), and biochemical properties including total soluble solids (11.36°Brix), titratable acidity (0.98%), ripening index (11.60), ascorbic acid (25.19 mg/100ml), total phenolic content (1.66 mg/100ml), and reduced enzyme activities PPO (0.58 Units/g/min) and POD (2.38 Units/g/min). Dark storage conditions also maintained fruit quality by minimizing oxidative degradation.

These findings are useful along the citrus supply chain for growers, packers and exporters since it contributes to minimizing losses, extending marketability, and maintaining fruit quality. Future studies should focus on new ecofriendly packaging materials, longer storage periods, smart monitoring technologies and the integration of these new tools with the other postharvest treatments. Determining the preferences of customers and evaluating environmental impacts will be useful in aligning innovations with market demands

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