

Effects of Storage Conditions on Postharvest Quality and Shelf Life of Tomato (*Solanum lycopersicum* L.) in Mekelle, Tigray, Ethiopia

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Abstract

Tomato (*Solanum lycopersicum* L.) is a highly perishable horticultural crop that experiences rapid physiological and biochemical deterioration after harvest, leading to significant postharvest losses, particularly in regions with limited cold-chain infrastructure. This study evaluated the effects of refrigeration, pot-in-pot evaporative cooling, and low-density polyethylene (LDPE) packaging on the postharvest quality and shelf life of tomato fruits under the environmental conditions of Mekelle, Tigray, Ethiopia. The experiment was conducted using a completely randomized design with three storage treatments and three replications. Quality attributes, including pH, weight loss, firmness, color development, decay incidence, and shelf life, were evaluated at 5-day intervals during storage. Data were subjected to one-way analysis of variance (ANOVA), and treatment means were compared using Tukey's honestly significant difference (HSD) test at $P < 0.05$. Storage conditions significantly influenced all evaluated quality parameters during storage. Refrigerated storage ($4 \pm 1^\circ\text{C}$; 85–90% relative humidity) provided the greatest preservation effect by reducing weight loss and decay development, maintaining firmness, delaying ripening-related changes, and extending marketable shelf life to 21 days. Pot-in-pot evaporative cooling also improved quality retention by providing a cooler and more humid storage environment without external energy requirements, extending shelf life to 19 days. In contrast, LDPE packaging under ambient conditions resulted in faster quality deterioration and maintained marketable quality for only 15 days. These findings demonstrate that refrigeration remains the most effective approach for long-term tomato preservation. However, pot-in-pot evaporative cooling represents a practical, low-cost, and energy-efficient alternative for warm regions where conventional refrigeration systems are limited. The adoption of suitable low-cost storage technologies can contribute to reducing postharvest losses and improving sustainable management of fresh tomato supply chains.

1. Introduction

Tomato (*Solanum lycopersicum* L.) is one of the most important vegetable crops worldwide due to its nutritional value, economic importance, and contribution to food security. It is a rich source of vitamins, minerals, dietary fiber, and bioactive compounds, including lycopene, carotenoids, flavonoids, and phenolics, which contribute to its health-promoting properties [6]; [11]. However, tomato is highly perishable because of its high moisture content, rapid respiration rate, and sensitive tissue structure. After harvest, continued respiration, transpiration, ethylene activity, and cell wall degradation accelerate ripening, softening, moisture loss, and microbial spoilage, leading to substantial postharvest losses [15]; [5]. Effective postharvest storage is essential for maintaining tomato quality and extending shelf life. Refrigeration is considered the most effective preservation method because it reduces metabolic activity, delays ripening, and limits quality deterioration. However, its application is often restricted in developing regions due to high investment costs, unreliable energy supply, and limited cold-chain infrastructure [5]. Therefore, affordable and energy-efficient storage technologies are increasingly needed to reduce postharvest losses under resource-limited conditions.

Pot-in-pot evaporative cooling is a promising low-cost technology that reduces storage temperature and increases relative humidity through evaporative water loss, thereby slowing physiological deterioration without requiring external energy input. Low-density polyethylene (LDPE) packaging can also reduce moisture loss and modify the storage environment, although its effectiveness depends on temperature conditions and packaging characteristics [10]. Previous studies have demonstrated the potential of evaporative cooling systems for maintaining the quality of horticultural commodities under warm climatic conditions [3]. In Ethiopia, tomato production contributes significantly to horticultural development; however, postharvest losses remain high due to inadequate storage facilities and limited access to cold-chain technologies [6]. This challenge is particularly relevant in northern Ethiopia, where high ambient temperatures accelerate fruit deterioration. Although refrigeration, evaporative cooling, and plastic packaging have been studied individually, comparative evaluations of these storage methods under the environmental conditions of northern Ethiopia are limited.

Therefore, this study evaluated the effects of refrigerated storage, pot-in-pot evaporative cooling, and LDPE packaging on the postharvest quality and shelf life of tomato fruits during 20 days of storage under the environmental conditions of Mekelle, Tigray, Ethiopia. Changes in pH, firmness, weight loss, color development, decay incidence, and shelf life were assessed to identify suitable storage technologies for reducing postharvest losses and improving tomato quality in regions with limited cold-chain infrastructure.

2. Materials and Methods

2.1. Sample collection and preparation

Fresh mature-green tomato (*Solanum lycopersicum* L.) fruits were purchased from a local market in Mekelle City, Tigray, Ethiopia. Mature-green fruits were selected to enable the evaluation of postharvest ripening, quality changes, and storage performance during the experimental period. To minimize biological variation, all fruits were obtained from a single vendor in one purchasing batch. The fruits were selected based on uniform size, shape, maturity, and freedom from visible defects. Fruits exhibiting mechanical damage, bruising, cracking, insect infestation, disease symptoms, or fungal infection were excluded. The selected tomatoes were transported to the Food Science and Postharvest Technology Laboratory, Mekelle University, within approximately 1 h under ambient conditions.

Upon arrival, the fruits were washed with distilled water to remove surface contaminants, air-dried at room temperature, and allowed to equilibrate to laboratory conditions before treatment allocation. The tomatoes were then randomly assigned to the respective storage treatments. Care was taken throughout sample preparation and handling to minimize mechanical injury and ensure uniformity among experimental units.

2.2. Storage treatments

The experiment was conducted using a completely randomized design (CRD) comprising three storage treatments with three replicates per treatment. Each replicate consisted of 10 tomato fruits, resulting in a total of 90 fruits (3 treatments $\times$ 3 replicates $\times$ 10 fruits). Following sample preparation and equilibration to laboratory conditions, the fruits were randomly allocated to the respective storage treatments. The storage treatments consisted of refrigerated storage (T_1), pot-in-pot evaporative cooling (T_2), and low-density polyethylene (LDPE) packaging (T_3). For refrigerated storage, fruits were stored in a laboratory refrigerator maintained at $4 \pm 1^\circ\text{C}$ and 85–90% relative humidity (RH) throughout the 20-day storage period.

The pot-in-pot evaporative cooling system consisted of a porous earthen pot placed inside a larger earthen pot, with the annular space between the pots filled with clean, moist sand. The system was installed in a naturally ventilated outdoor area, and water was added twice daily to maintain sand moisture and sustain evaporative cooling. Storage temperature and relative humidity were monitored daily using a calibrated digital thermo-hygrometer (HTC-1; HTC Instruments, China). During the storage period, the average temperature inside the evaporative cooling unit was 22°C , compared with an average ambient temperature of 35°C . The corresponding average relative humidity was 85% inside the cooling unit and 35% under ambient conditions. For the LDPE packaging treatment, each replicate of 10 fruits was packed in a 50- μm low-density polyethylene (LDPE) bag and stored under ambient laboratory conditions ($25\text{--}30^\circ\text{C}$ and 50–70% RH).

The storage experiment lasted 20 days, and fruit quality was evaluated at 5-day intervals (Days 0, 5, 10, 15, and 20). Percentage weight loss was determined non-destructively using the same tagged fruits throughout the storage period. In contrast, pH and firmness were measured destructively using representative fruits randomly selected from each replicate at each sampling interval. The pH meter and penetrometer were calibrated before each measurement according to the manufacturers' instructions to ensure measurement accuracy. Color development, decay incidence, and marketable shelf life were assessed using the methods described in the subsequent sections.

2.3. PH Determination

The pH of tomato fruits was determined according to the Official Method of Analysis described by [1]. Measurements were performed at 5-day intervals (Days 0, 5, 10, 15, and 20). Because pH determination is a destructive analysis, representative fruits were randomly selected from each replicate at each sampling interval. The selected fruits were washed with distilled water, cut into small pieces, and homogenized using a laboratory blender to obtain a uniform juice sample. Approximately 10 mL of the homogenized juice was transferred into a clean beaker, and the pH was measured using a calibrated digital pH meter (PHS-3E; INESA Scientific Instrument Co., China). The pH meter was calibrated before each analytical session using standard buffer solutions (pH 4.00 and 7.00) according to the manufacturer's instructions. All measurements were performed at room temperature (approximately $25 \pm 2^\circ\text{C}$). The electrode was rinsed with distilled water and gently blotted dry between successive measurements to prevent cross-contamination. Each sample was analyzed in triplicate, and the results were expressed as mean $\pm$ standard deviation (SD).

2. 4. Weight Loss Determination

Weight loss was determined using a non-destructive method by measuring the mass of individually labeled tomato fruits at the beginning of storage (Day 0) and subsequently at 5-day intervals (Days 5, 10, 15, and 20). The same fruits were weighed throughout the storage period using a calibrated digital analytical balance to monitor cumulative weight loss. Before each measurement, fruits were gently wiped with a clean, dry tissue to remove any surface moisture without causing mechanical damage. Percentage weight loss was calculated according to the following equation:

Weight loss (%) = $\frac{W_i - W_t}{W_i} \times 100$, Where, W_i = initial weight (g) (W_i) = initial fruit weight before storage (g)

(W_t) = fruit weight at each sampling interval (g).

2.5. Firmness Determination

Fruit firmness was determined using a hand-held fruit penetrometer (PCE-PTR 200, PCE Instruments, Germany) at 5-day intervals during storage (Days 0, 5, 10, 15, and 20). Since firmness measurement is a destructive analysis, separate representative fruits were randomly selected from each replicate at each sampling interval. Prior to measurement, a small area of the peel was carefully removed from two opposite equatorial positions of each fruit to expose the flesh tissue. Firmness was measured by inserting an 8-mm diameter probe perpendicular to the fruit surface at a constant rate to a penetration depth of 10 mm. Two measurements were taken from opposite equatorial sides of each fruit, and the mean value was recorded as the firmness of the sample. Firmness values were expressed in Newtons (N). All measurements were performed in triplicate, and results were presented as mean $\pm$ standard deviation (SD).

2.6. Color Development Assessment

Color development of tomato fruits was evaluated visually at 5-day intervals during storage (Days 0, 5, 10, 15, and 20). As color assessment was a non-destructive evaluation, the same individually tagged fruits were monitored throughout the storage period. Ten fruits from each replicate were evaluated for each storage treatment under uniform laboratory lighting conditions to minimize variation in visual assessment. Fruit color was categorized according to visible ripening stages as pink, light pink, bright red, and deep red (fully ripe). At each sampling interval, the number of fruits in each color category was recorded, and the results were expressed as mean values $\pm$ standard deviation (SD).

2.7. Decay Incidence Assessment

Decay incidence of tomato fruits was evaluated visually at 5-day intervals during storage (Days 0, 5, 10, 15, and 20). As decay assessment was a non-destructive evaluation, the same individually tagged fruits were monitored throughout the storage period. Ten fruits from each replicate were assessed for each storage treatment under uniform laboratory lighting conditions to ensure consistent visual evaluation.

Fruits were classified into four categories based on the severity of deterioration: no decay, slight decay, moderate decay, and severe decay. Fruits without visible lesions, fungal growth, or tissue deterioration were categorized as no decay. Fruits exhibiting minor localized lesions or slight surface discoloration were classified as slight decay. Fruits showing clear decay symptoms accompanied by moderate tissue deterioration were categorized as moderate decay, whereas fruits with extensive fungal growth, severe tissue breakdown, or unacceptable visual quality were classified as severe decay. The number of fruits exhibiting visible decay symptoms (slight, moderate, or severe decay) was recorded at each sampling interval. Decay incidence was calculated using the following equation:

Decay incidence (%) = $\frac{\text{number of decayed fruits}}{\text{total number of fruits evaluated}} \times 100$, where decayed fruits refer to those showing any visible deterioration symptoms, including slight, moderate, or severe decay. The results were expressed as mean $\pm$ standard deviation (SD).

2.8. Shelf Life Determination

Shelf life was defined as the duration during which tomato fruits retained acceptable market quality under each storage treatment. It was determined based on visual and physical quality attributes, including color development, decay incidence, firmness retention, shriveling, and overall market acceptability. Evaluations were conducted at 5-day intervals during storage (Days 0, 5, 10, 15, and 20) using the same individually tagged fruits throughout the monitoring period. Tomato fruits were considered to have reached the end of their marketable shelf life when they exhibited severe shriveling, excessive softening, visible decay symptoms, or unacceptable external appearance that limited their suitability for sale and consumption. Although physicochemical analyses were conducted up to Day 20, fruits were continuously monitored until they no longer met the defined criteria for market acceptability. Shelf life was recorded as the number of days elapsed from the start of storage until the fruits became unmarketable. The average shelf life for each storage treatment was calculated and expressed as mean $\pm$ standard deviation (SD).

2.9. Experimental Design and Statistical Analysis

The experiment was conducted using a completely randomized design (CRD) comprising three storage treatments: refrigerated storage (T_1), pot-in-pot evaporative cooling (T_2), and plastic packaging (T_3). Each treatment included three independent replicates, with 10 tomato fruits per replicate, resulting in a total of 90 fruits. Fruits with uniform size and maturity were randomly allocated to the respective storage treatments. Tomatoes were stored for 20 days, and quality evaluations were performed at 5-day intervals (Days 0, 5, 10, 15, and 20). Weight loss, color development, decay incidence, and shelf life were evaluated non-destructively using the same individually tagged fruits throughout storage. In contrast, pH and firmness measurements were conducted destructively using representative fruits randomly selected from each replicate at each sampling interval.

All experimental data were expressed as mean $\pm$ standard deviation (SD) based on three independent replicates. Statistical analyses were performed using SPSS Statistics version 20.0 (IBM Corp., Armonk,

NY, USA). One-way analysis of variance (ANOVA) was used to determine the effect of storage treatments on each quality parameter at each evaluation period. When significant differences were observed, treatment means were separated using Tukey's honestly significant difference (HSD) test at a significance level of $p < 0.05$.

3. Results and Discussion

3.1. Effect of Storage Conditions on Tomato pH

The effects of different storage conditions on tomato fruit pH during storage are presented in Table 1. Initial pH values (Day 0) were not significantly different among storage treatments ($P > 0.05$), indicating that fruits had comparable maturity and initial physiological quality before storage. However, significant differences among treatments were observed from Day 5 onward ($P < 0.05$), confirming that storage conditions influenced acidity changes during ripening and storage. Tomato pH showed an initial decline during the first five days of storage, followed by a progressive increase during subsequent storage across all treatments.

The initial decrease may be related to short-term postharvest metabolic adjustments, whereas the later increase reflects a gradual reduction in acidity caused by the utilization and degradation of organic acids, particularly citric and malic acids, during ripening and senescence. Similar changes in tomato acidity during storage have been reported by [14]. And are consistent with postharvest physiological processes described by [13]. The magnitude of pH changes varied among storage environments. Refrigerated fruits exhibited the slowest increase in pH, changing from 3.38 on Day 5 to 4.58 on Day 20. The delayed increase in pH under refrigeration can be attributed to reduced respiration and slower ripening-associated biochemical reactions, which minimize organic acid degradation. Low-temperature storage is widely recognized for maintaining fruit chemical quality by reducing metabolic activity and delaying senescence-related changes [7]; [17] .

Pot-in-pot evaporative cooling provided intermediate protection against acidity loss. Fruits stored under this system reached a pH of 4.80 by Day 15, compared with 5.10 in LDPE-packaged fruits. The improved pH retention under evaporative cooling was likely associated with the lower storage temperature (approximately 22°C) and high relative humidity (~ 85%), which reduced respiration and delayed ripening compared with warmer storage conditions. Similar studies have demonstrated that evaporative cooling can preserve physicochemical quality and delay ripening of horticultural commodities under warm climatic conditions [16]; [12].

LDPE packaging resulted in the greatest increase in pH, reaching 5.10 by Day 15. Although LDPE packaging can reduce moisture loss by maintaining a humid microenvironment, it provides limited control over storage temperature. Under relatively warm conditions, continued metabolic activity accelerates ripening and organic acid degradation, resulting in faster acidity loss. This supports previous findings that packaging technologies are most effective when combined with appropriate temperature

management [10]. No pH measurements were obtained for pot-in-pot and LDPE treatments on Day 20 because fruits from these treatments had exceeded their marketable shelf life before the final evaluation. This observation further indicates the ability of refrigerated storage to maintain acceptable tomato quality for a longer period.

Overall, storage temperature and environmental control played a critical role in regulating tomato acidity changes during storage. Refrigeration provided the greatest preservation of pH stability, while pot-in-pot evaporative cooling effectively slowed acidity loss compared with LDPE packaging, demonstrating its potential as a low-cost approach for maintaining tomato chemical quality under warm storage conditions.

Table 1
Effect of storage conditions on the pH of tomato fruits during storage (Mean ± SD)

Storage treatment	Day 0	Day 5	Day 10	Day 15	Day 20
Pot-in-pot	3.97 ± 0.03 ^a	3.60 ± 0.05 ^b	4.67 ± 0.04 ^c	4.80 ± 0.06 ^c	–
Plastic packaging (LDPE)	3.97 ± 0.04 ^a	3.72 ± 0.03 ^b	4.71 ± 0.05 ^c	5.10 ± 0.07 ^c	–
Refrigeration	3.97 ± 0.02 ^a	3.38 ± 0.04 ^b	4.41 ± 0.03 ^c	4.46 ± 0.05 ^c	4.58 ± 0.04 ^c
P-value	> 0.05	0.031	0.012	0.001	NA

Note: Values are expressed as mean ± standard deviation (SD) (n = 3). Within each storage interval, means followed by different superscript letters indicate significant differences among storage treatments according to Tukey’s honestly significant difference (HSD) test at *P* < 0.05. “–” indicates that fruits exceeded their marketable shelf life before Day 20 and were therefore unavailable for analysis. NA = not applicable because statistical comparison among treatments could not be performed as only refrigerated fruits remained available on Day 20.

3.2. Effect of Storage Conditions on Tomato Firmness

The effects of different storage conditions on tomato fruit firmness during storage are presented in Table 2. Initial firmness values (Day 0) showed no significant differences among treatments (*P* > 0.05), indicating that fruits had comparable initial textural characteristics before storage. However, significant differences among storage treatments were observed from Day 5 onward (*P* < 0.05), confirming that storage conditions influenced firmness retention during postharvest storage.

Firmness declined progressively in all treatments as ripening advanced; however, the rate of softening differed among storage environments. Refrigerated fruits maintained the highest firmness throughout storage, decreasing from 4.50 N at harvest to 3.00 N after 20 days. Pot-in-pot evaporative cooling showed intermediate performance, retaining firmness of 3.00 N by Day 15, whereas LDPE-packaged fruits exhibited the greatest firmness loss, declining to 2.30 N by Day 15 and exceeding their marketable shelf life before Day 20.

The reduction in tomato firmness during storage is primarily associated with ripening-related structural changes in the cell wall. During ripening, increased activities of cell wall-modifying enzymes, including polygalacturonase, pectin methylesterase, and β -galactosidase, promote pectin solubilization and degradation of cell wall components, resulting in reduced tissue strength and fruit softening [4]; [17]. In addition, moisture loss during storage contributes to reduced cell turgor, further accelerating firmness decline.

Refrigerated storage provided the greatest firmness retention, which can be attributed to reduced respiration and delayed ripening progression under low-temperature conditions. Lower temperatures slow metabolic reactions and reduce the rate of biochemical processes associated with cell wall degradation, thereby maintaining fruit tissue integrity for a longer period [7]; [17] Similar improvements in firmness preservation of tomatoes under refrigerated conditions have been reported by [14].

Pot-in-pot evaporative cooling maintained higher firmness than LDPE packaging by creating a more favorable storage environment. The system reduced storage temperature from approximately 35°C under ambient conditions to about 22°C while maintaining high relative humidity (~ 85%). These conditions likely reduced transpiration, helped maintain cell turgor, and slowed ripening-related softening compared with warmer storage conditions. Similar benefits of evaporative cooling for maintaining firmness and extending the storage quality of horticultural commodities have been reported under warm-climate conditions [16]; [8].

In contrast, LDPE packaging resulted in the greatest firmness loss despite reducing moisture loss. The limited ability of packaging to control temperature allowed continued metabolic activity, accelerated ripening, and increased cell wall degradation, leading to faster softening. This supports previous findings that packaging alone cannot effectively maintain tomato quality when temperature management is inadequate [10] ; [7].

Overall, storage conditions strongly influenced the rate of tomato softening during storage. Refrigeration provided the greatest preservation of structural quality, while pot-in-pot evaporative cooling delayed firmness loss compared with LDPE packaging, demonstrating its potential as a low-cost strategy for maintaining tomato textural quality under warm storage conditions.

Table 2
Effect of storage conditions on firmness (N) of tomato fruits during storage (Mean $\pm$ SD)

Storage treatment	Day 0	Day 5	Day 10	Day 15	Day 20
Pot-in-pot evaporative cooling	4.50 $\pm$ 0.04 ^a	4.30 $\pm$ 0.05 ^a	3.40 $\pm$ 0.06 ^a	3.00 $\pm$ 0.05 ^a	–
Plastic packaging	4.50 $\pm$ 0.03 ^a	3.10 $\pm$ 0.04 ^a	2.90 $\pm$ 0.05 ^a	2.30 $\pm$ 0.06 ^a	–
Refrigeration	4.50 $\pm$ 0.02 ^a	4.40 $\pm$ 0.03 ^a	3.80 $\pm$ 0.04 ^a	3.30 $\pm$ 0.05 ^a	3.00 $\pm$ 0.04 ^a
P-value	> 0.05	< 0.05	< 0.05	< 0.05	NA
Note: Values are expressed as mean $\pm$ standard deviation (SD) (n = 3). Within each storage interval, means followed by different superscript letters indicate significant differences among storage treatments according to Tukey's honestly significant difference (HSD) test at $P < 0.05$. "–" indicates that fruits exceeded their marketable shelf life before Day 20 and were therefore unavailable for firmness determination. NA = not applicable because only refrigerated fruits remained available for evaluation on Day 20.					

3.3. Effect of Storage Conditions on Percentage Weight Loss of Tomato Fruits

The effect of different storage conditions on percentage weight loss of tomato fruits during storage is presented in Table 3. Initial weight loss values (Day 0) were not significantly different among treatments ($P > 0.05$), indicating similar initial fruit mass and physiological conditions before storage. However, significant differences among storage treatments were observed from Day 5 onward ($P < 0.05$), demonstrating that storage environment strongly influenced moisture loss during storage.

Weight loss increased progressively in all treatments, although the rate differed considerably among storage conditions. Refrigerated fruits exhibited the lowest weight loss, increasing from 7.00% on Day 5 to 15.80% after 20 days. Pot-in-pot evaporative cooling showed intermediate performance, with weight loss reaching 18.00% by Day 15, whereas LDPE-packaged fruits recorded the highest weight loss (25.00% by Day 15) and exceeded their marketable shelf life before Day 20.

Postharvest weight loss in tomato fruits is mainly caused by water loss through transpiration and the consumption of stored substrates during respiration. The extent of moisture loss is influenced by storage temperature, relative humidity, and the vapor pressure difference between fruit tissues and the surrounding environment [2] ; [10]. Excessive water loss reduces cell turgor, resulting in shriveling, firmness reduction, and deterioration of visual quality.

The lower weight loss observed under refrigeration can be attributed to the reduced temperature and controlled humidity environment, which decreased transpiration and slowed respiratory activity. Low-temperature storage reduces water vapor movement and metabolic reactions, thereby delaying moisture loss and physiological deterioration in fresh produce [15]; [5].

Pot-in-pot evaporative cooling also reduced weight loss compared with LDPE packaging. The system maintained a lower storage temperature (approximately 22°C) and high relative humidity (~ 85%), conditions that likely reduced moisture diffusion from fruit tissues and helped maintain cellular water balance. These results demonstrate the potential of evaporative cooling as an energy-efficient and affordable technology for minimizing postharvest losses in warm regions where conventional refrigeration is limited [9].

In contrast, LDPE packaging resulted in the highest weight loss despite its ability to reduce direct moisture exchange. Under warm storage conditions, packaging alone could not adequately control temperature-driven respiration and ripening processes. The combination of elevated temperature and continued metabolic activity likely accelerated physiological deterioration, contributing to greater quality loss [10].

Overall, storage conditions significantly affected moisture retention in tomato fruits. Refrigeration provided the greatest reduction in weight loss, while pot-in-pot evaporative cooling improved water retention compared with LDPE packaging, demonstrating its potential for reducing postharvest moisture losses under warm storage conditions.

Table 3
Effect of storage conditions on weight loss (%) of tomato fruits during storage (Mean ± SD)

Storage treatment	Day 0	Day 5	Day 10	Day 15	Day 20
Pot-in-pot evaporative cooling	0.00 ± 0.00 ^a	8.00 ± 0.04 ^b	11.00 ± 0.04 ^b	18.00 ± 0.04 ^b	–
Plastic packaging (LDPE)	0.00 ± 0.00 ^a	12.00 ± 0.04 ^b	15.00 ± 0.04 ^b	25.00 ± 0.04 ^b	–
Refrigeration	0.00 ± 0.00 ^a	7.00 ± 0.04 ^b	8.00 ± 0.04 ^b	14.00 ± 0.04 ^b	15.80 ± 0.04 ^b
P-value	> 0.05	0.027	0.011	0.002	NA

Note: Values are expressed as mean ± standard deviation (SD) (n = 3). Within each storage interval, means followed by different superscript letters indicate significant differences among storage treatments according to Tukey’s honestly significant difference (HSD) test at *P* < 0.05. “–” indicates that fruits exceeded their marketable shelf life before Day 20 and were therefore unavailable for analysis. NA = not applicable because statistical comparison among treatments could not be performed as only refrigerated fruits remained available on Day 20.

3.4. Effect of Storage Conditions on Color Development of Tomato Fruits

The effect of different storage conditions on tomato fruit color development during storage is presented in Table 4. Tomato fruits progressively changed from the pink stage to the deep red (fully ripe) stage, reflecting normal ripening progression after harvest. However, the rate of color transition differed among

storage treatments, indicating that storage conditions influenced ripening behavior and maintenance of visual quality.

Refrigerated fruits exhibited the slowest color development throughout storage. On Day 5, most refrigerated fruits remained at the pink stage (8.00 fruits), and no fruits had reached the deep red stage by Day 15. Even after 20 days, only a limited number of fruits reached full ripeness (1.50 fruits), indicating delayed ripening under refrigerated conditions. The slower color development under refrigeration can be attributed to reduced respiration and delayed ethylene-mediated ripening processes, which slow chlorophyll degradation and carotenoid accumulation, particularly lycopene synthesis responsible for tomato red coloration [13].

Pot-in-pot evaporative cooling showed an intermediate effect on ripening progression. Fruits gradually advanced from the pink stage to more advanced ripening stages, with 5.00 fruits reaching the bright red stage and only 1.00 fruit reaching the deep red stage by Day 15. The delayed color transition under evaporative cooling was likely associated with the lower storage temperature (approximately 22°C) and high relative humidity (~ 85%), which reduced metabolic activity and slowed ripening-related biochemical changes compared with warmer storage conditions. Similar benefits of evaporative cooling for maintaining postharvest quality and delaying ripening of horticultural commodities have been reported under warm climatic conditions [7]; [13].

In contrast, LDPE-packaged fruits showed faster color development during storage. By Day 15, a greater proportion of fruits had reached advanced ripening stages, including 5.50 fruits at the bright red stage and 3.00 fruits at the deep red stage. Although LDPE packaging reduces moisture loss by maintaining a humid microenvironment, it does not provide sufficient temperature control. Consequently, continued respiration and ethylene activity under warmer conditions accelerate chlorophyll degradation and carotenoid accumulation, resulting in faster color development and reduced storage life. Similar observations have shown that packaging alone is less effective for delaying tomato ripening when appropriate temperature management is lacking [10].

Overall, storage temperature played a major role in regulating tomato color development during storage. Refrigeration most effectively delayed ripening-related color changes, while pot-in-pot evaporative cooling slowed pigment development compared with LDPE packaging, demonstrating its potential for maintaining visual quality under warm storage conditions.

Table 4

Effect of storage conditions on the distribution of tomato fruits among different ripening stages during storage (Mean number of fruits $\pm$ SD, n = 3)

Storage treatment	Storage day	Pink stage	Light pink stage	Bright red stage	Deep red (fully ripe) stage
Pot-in-pot evaporative cooling	Day 5	7.00 $\pm$ 0.58 ^a	3.00 $\pm$ 0.58 ^a	0.00 $\pm$ 0.00 ^a	0.00 $\pm$ 0.00 ^a
	Day 10	2.50 $\pm$ 0.50 ^a	5.50 $\pm$ 0.50 ^a	2.00 $\pm$ 0.58 ^a	0.00 $\pm$ 0.00 ^a
	Day 15	0.80 $\pm$ 0.29 ^a	3.20 $\pm$ 0.58 ^a	5.00 $\pm$ 0.58 ^a	1.00 $\pm$ 0.00 ^a
	Day 20	–	–	–	–
Plastic packaging	Day 5	5.00 $\pm$ 0.58 ^a	4.00 $\pm$ 0.58 ^a	1.00 $\pm$ 0.00 ^a	0.00 $\pm$ 0.00 ^a
	Day 10	1.50 $\pm$ 0.50 ^a	3.00 $\pm$ 0.58 ^a	4.50 $\pm$ 0.50 ^a	1.00 $\pm$ 0.00 ^a
	Day 15	–	1.50 $\pm$ 0.50 ^a	5.50 $\pm$ 0.50 ^a	3.00 $\pm$ 0.58 ^a
	Day 20	–	–	–	–
Refrigeration	Day 5	8.00 $\pm$ 0.58 ^a	2.00 $\pm$ 0.58 ^a	0.00 $\pm$ 0.00 ^a	0.00 $\pm$ 0.00 ^a
	Day 10	5.00 $\pm$ 0.58 ^a	4.00 $\pm$ 0.58 ^a	1.00 $\pm$ 0.00 ^a	0.00 $\pm$ 0.00 ^a
	Day 15	2.50 $\pm$ 0.50 ^a	5.00 $\pm$ 0.58 ^a	2.50 $\pm$ 0.50 ^a	0.00 $\pm$ 0.00 ^a
	Day 20	0.50 $\pm$ 0.50 ^a	3.00 $\pm$ 0.58 ^a	5.00 $\pm$ 0.58 ^a	1.50 $\pm$ 0.50 ^a

Note: Values are expressed as mean number of fruits $\pm$ standard deviation (SD) (n = 3). Within each storage day and ripening stage, means followed by different superscript letters indicate significant differences among storage treatments according to Tukey's honestly significant difference (HSD) test at $P < 0.05$. "–" indicates that fruits exceeded their marketable shelf life before the respective evaluation day and were therefore unavailable for assessment.

3.5. Effect of Storage Conditions on Decay Incidence of Tomato Fruits

The effect of different storage conditions on decay incidence of tomato fruits during storage is presented in Table 5. No visible decay was observed in any treatment at harvest (Day 0), indicating that fruits had comparable initial quality before storage. However, significant differences among storage treatments were observed from Day 5 onward ($P < 0.05$), demonstrating that storage conditions influenced the progression of postharvest deterioration.

Decay incidence increased progressively during storage, although the rate of deterioration differed among treatments. Refrigerated fruits exhibited the lowest decay development, with no visible decay until Day 10 and only 6.67% and 13.33% decay on Days 15 and 20, respectively. Pot-in-pot evaporative cooling showed intermediate performance, with decay incidence increasing to 3.33% on Day 10 and 10.00% on Day 15. In contrast, LDPE-packaged fruits showed the highest decay incidence, reaching 16.67% on Day 10 and 30.00% on Day 15, after which fruits exceeded their marketable shelf life before Day 20.

The reduced decay incidence under refrigeration was associated with delayed physiological deterioration under low-temperature conditions. Refrigeration reduces respiration rate, slows ripening-related changes, and helps maintain tissue integrity, thereby reducing fruit susceptibility to decay-causing microorganisms [7] ; [13]. The lower decay development observed in refrigerated fruits was also consistent with their lower weight loss, improved firmness retention, delayed color development, and longer shelf life observed in this study.

Pot-in-pot evaporative cooling also reduced decay development compared with LDPE packaging. The system maintained a lower storage temperature (approximately 22°C) and high relative humidity (~ 85%), which helped reduce moisture loss, maintain cellular integrity, and delay senescence. Although high humidity can potentially promote microbial growth, the combined effects of reduced temperature and improved physiological condition of the fruits contributed to lower decay incidence compared with warmer storage conditions. Similar benefits of evaporative cooling in reducing postharvest deterioration of fresh horticultural commodities have been reported under warm-climate conditions [9].

In contrast, LDPE packaging resulted in the highest decay incidence despite its ability to reduce moisture loss. The lack of temperature control under ambient conditions allowed continued respiration, accelerated ripening, and increased tissue softening, creating conditions favorable for microbial infection and decay development. These findings support previous reports that packaging alone is insufficient to maintain tomato quality when storage temperature is not adequately controlled [10].

Overall, storage temperature and environmental conditions strongly influenced decay progression during tomato storage. Refrigeration provided the greatest protection against decay development, while pot-in-pot evaporative cooling delayed deterioration compared with LDPE packaging, demonstrating its potential for maintaining tomato quality under resource-limited storage conditions.

Table 5

Effect of storage conditions on decay incidence of tomato fruits during storage (Mean $\pm$ SD, n = 3)

Storage treatment	Day 0	Day 5	Day 10	Day 15	Day 20
Pot-in-pot evaporative cooling	0.00 $\pm$ 0.00 ^a	0.00 $\pm$ 0.00 ^a	3.33 $\pm$ 1.15 ^b	10.00 $\pm$ 2.00 ^c	–
Plastic packaging (LDPE)	0.00 $\pm$ 0.00 ^a	6.67 $\pm$ 1.15 ^b	16.67 $\pm$ 2.89 ^c	30.00 $\pm$ 5.77 ^d	–
Refrigeration	0.00 $\pm$ 0.00 ^a	0.00 $\pm$ 0.00 ^a	0.00 $\pm$ 0.00 ^a	6.67 $\pm$ 1.15 ^b	13.33 $\pm$ 2.31 ^c
P-value	> 0.05	< 0.05	< 0.05	< 0.05	NA
Note: Values are expressed as mean decay incidence (%) $\pm$ standard deviation (SD) (n = 3). Within each storage interval, means followed by different superscript letters indicate significant differences among storage treatments according to Tukey's honestly significant difference (HSD) test at $P < 0.05$. "–" indicates that fruits exceeded their marketable shelf life before Day 20 and were therefore unavailable for evaluation. NA = not applicable because statistical comparison among storage treatments could not be performed as only refrigerated fruits remained available on Day 20.					

3.6. Effect of Storage Conditions on Shelf Life of Tomato Fruits

The effects of different storage conditions on tomato fruit shelf life are presented in Table 6. Storage treatments significantly influenced shelf life ($P < 0.05$). Refrigerated storage resulted in the longest shelf life (21.0 ± 1.00 days), followed by pot-in-pot evaporative cooling (19.0 ± 1.00 days), whereas LDPE packaging resulted in the shortest shelf life (15.0 ± 1.00 days). These findings demonstrate the importance of temperature and storage environment in delaying postharvest deterioration and maintaining tomato marketability.

The extended shelf life under refrigeration was associated with reduced physiological activity under low-temperature conditions. Refrigeration slows respiration, delays ethylene-mediated ripening, reduces moisture loss, and delays quality deterioration, thereby contributing to better firmness retention, slower color development, reduced decay incidence, and prolonged marketable quality [7] ; [13]. The longer storage duration observed under refrigeration reflects the combined preservation effects observed across the physicochemical and visual quality parameters evaluated in this study.

Pot-in-pot evaporative cooling extended shelf life by four days compared with LDPE packaging, demonstrating its potential as a low-cost preservation approach for warm-climate regions. The reduced storage temperature (approximately 22°C) and high relative humidity (~ 85%) provided by the evaporative cooling system likely reduced transpiration, slowed ripening progression, and delayed deterioration processes. Similar improvements in tomato shelf life and quality retention under evaporative cooling conditions have been reported under tropical and warm-climate storage environments [9] ; [12]. Although LDPE packaging reduced moisture loss, it resulted in the shortest shelf life. The limited ability of packaging to control storage temperature allowed continued metabolic activity, accelerated ripening,

greater firmness loss, and increased decay development, resulting in earlier loss of marketable quality. This confirms that packaging technologies are most effective when combined with appropriate temperature management [10].

Overall, storage temperature and environmental management were critical determinants of tomato shelf life. Refrigeration provided the most effective preservation strategy, while pot-in-pot evaporative cooling demonstrated considerable potential as an affordable and energy-efficient alternative for extending tomato marketability in regions where conventional cold-chain facilities are limited

Table 6
Effect of storage conditions on shelf life of tomato fruits (Mean ± SD, n = 3)

Storage method	Shelf life (days)
Plastic packaging (LDPE)	15.0 ± 1.00 ^a
Pot-in-pot evaporative cooling	19.0 ± 1.00 ^b
Refrigeration	21.0 ± 1.00 ^c
P-value	0.003
Note: Values are expressed as mean shelf life (days) ± standard deviation (SD) (n = 3). Means followed by different superscript letters indicate significant differences among storage treatments according to Tukey's honestly significant difference (HSD) test at <i>P</i> < 0.05.	

4. Conclusions

This study demonstrated that storage conditions significantly influenced the postharvest quality and shelf life of tomato fruits by regulating ripening, physicochemical changes, and deterioration processes during storage. Refrigerated storage provided the most effective preservation performance, maintaining fruit quality attributes and extending marketable shelf life to 21 days. Pot-in-pot evaporative cooling showed considerable potential as a sustainable and low-cost postharvest preservation technology, extending tomato shelf life to 19 days and providing better quality retention than LDPE packaging under the warm environmental conditions of Mekelle, Ethiopia. Its effectiveness was associated with the ability to provide a cooler and more humid storage environment, thereby slowing ripening and delaying quality deterioration. In contrast, LDPE packaging under ambient conditions was less effective because it reduced moisture loss without providing adequate temperature control, resulting in faster deterioration and a shorter shelf life (15 days).

Overall, refrigeration remains the most reliable option for long-term tomato preservation where cold-chain facilities are available. However, pot-in-pot evaporative cooling represents a practical, energy-efficient, and environmentally sustainable alternative for regions with limited access to conventional refrigeration. The adoption of such low-cost cooling technologies could contribute to reducing postharvest losses, improving food quality preservation, and supporting more sustainable postharvest management systems in warm-climate regions.

Declarations

Competing Interests

The authors declare that there are no financial or non-financial competing interests regarding the publication of this article

Clinical Trial Number

Not applicable

Ethics

The, ethical approval was reviewed by the local Ethics Committee of the Mekelle University Research Academy, in accordance with its established guidelines. The reflective nature of the study and the fact that all procedures performed were part of standard care contributed to this decision. The research protocol for this study was approved by the University Research Ethics Committee of Mekelle University Research Academy). All procedures were conducted in accordance with the ethical standards of the committee Mekelle University Research Academy Declaration and Informed consent was obtained from all participants prior to data collection. The study adhered strictly to the ethical guidelines set by the Mekelle University Research Academy.

Consent to publish

Not applicable

Plant guide line

I have used local plant guideline

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Author Contribution

Kidanemariam conceived and designed the study, conducted the experiments, collected and analyzed the data, interpreted the results, and drafted the manuscript. Ftwi .Contributed to the study design, supervised the research, assisted with data interpretation, and critically reviewed and edited the manuscript. gebrehiwot. Contributed to the experimental methodology, statistical analysis, and interpretation of the findings, and reviewed the manuscript. Iijalem. Assisted with laboratory work, contributed to data validation and manuscript revision, and reviewed the final version of the manuscript. All authors read and approved the final manuscript.

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Data Availability

The datasets generated during and/or analyzed during the current study are available in the manuscript.

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