

Postharvest Management of Tomatoes (*Solanum lycopersicum*): A PRISMA-Guided Review of Storage Techniques and Quality Outcomes

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Abstract

*Due to improper handling and inadequate storage system, postharvest losses in developing countries are as high as 50% for the nutrient-rich but perishable tomato (*Solanum lycopersicum*). This systematic review, conducted in line with PRISMA guidelines and founded on a targeted literature search of Scopus, PubMed, Science Direct, and Google Scholar (2013–2025), aimed to identify good storage practices and their effects on tomato quality. Six terms were utilized, and studies were included based on relevance, peer-review status, and focus on comparative storage outcomes. Five storage techniques, cold storage, evaporative cooling, ambient storage, refrigeration, and modified atmosphere packaging (MAP), were compared with an emphasis on the impact of storage on nutritional, physical, microbiological, and economic quality of tomatoes. Trial and reviewed paper evidence suggested that while refrigeration and MAP both maintain vitamin C and lycopene content well, their use is often limited by cost and infrastructure constraints under low-resource conditions. Cold storage, while resource-demanding, remains optimal for long-term preservation. Evaporative cooling provides a low-cost alternative, reducing spoilage and weight loss modestly under rural conditions. Ambient storage, although most practiced, contributes significantly to degradation and microbial growth. Emerging and new technologies such as IoT monitoring, predictive microbial modeling, and metabolomics open up new avenues to optimize postharvest outcomes. Ultimately, this review identifies the need for context-specific, sustainable storage solutions that are a compromise of cost, availability, and technology, and proposes localized interventions to reduce tomato losses across diverse value chains and climates.*

Keywords: Evaporative cooling, Microbial spoilage, Modified atmosphere packaging, Postharvest quality, Tomato storage

Introduction

Tomato (*Solanum lycopersicum*) is a widely cultivated horticultural crop globally, valued for its nutritional quality and culinary use (Panno et al., 2021). Tomato is a key contributor of dietary micronutrients such as vitamin C, folate, and potassium, and antioxidant phytochemicals including lycopene, β -carotene, flavonoids, and phenolic compounds (Raiola et al., 2014; Pinela et al., 2022). These bioactive contents have been strongly associated with health benefits, including prevention and therapy for cardiovascular diseases, prostate cancer, and other oxidative stress (Perea-Domínguez et al., 2018; Ilahy et al., 2019).

Lycopene and quercetin are among the constituents receiving significant scientific interest. Lycopene, a carotenoid, is linked with reduced risks of chronic diseases. At the same time, quercetin, a flavonoid, exerts antioxidant and anti-inflammatory effects through the modulation of inflammatory pathways, elimination of Reactive Oxygen Species (ROS), and inhibition of cancer cell proliferation (Perea-Domínguez et al., 2018; Batiha et al., 2020). These nutrients underscore the critical role of tomato production in increasing food and nutrition security, particularly for tropical and subtropical regions where the crop is economically extremely vital (Raiola et al., 2014).

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While it is healthy, the tomato is highly perishable due to its soft nature and water content (~94–95%). It is a climacteric fruit that ripens quickly, a phenomenon that enhances postharvest spoilage (Haile et al., 2018; Siddiqui et al., 2018). In developing countries, postharvest handling practices vary; high ambient temperatures, poor storage facilities, and weak cold-chain systems contribute to losses between 20% and 50%, resulting in economic loss and diversion of valuable nutrients from the food supply (FAO, 2021). Transportation issues and poor infrastructure additionally contribute to these losses.

Physiological and environmental interactions of varied complexity form the basis of tomato spoilage, including high respiration rate, microbial contamination, mechanical injury, temperature, humidity, and light stress (Ali et al., 2021; Umeohia et al., 2024). These not only cause the fruit's texture, color, and appearance to deteriorate but also reduce its nutritional quality and susceptibility to fungal and bacterial infection.

Consequently, storage technologies have been designed along value cold chain storage, refrigeration, evaporative cooling, modified atmosphere packaging (MAP), and ambient storage, differing in their effectiveness levels, technological requirements, and cost components (Opara & Mditshwa, 2013). MAP and cold storage are beneficial in preserving tomato quality; their high energy and infrastructure demands make them less sustainable in low-resource settings.

Therefore, selecting an appropriate storage practice must balance technical efficiency, economic viability, environmental acceptability, and social acceptability. In this review, a comparative analysis of some of the tomato storage practices in relation to their impact on the most critical quality parameters, i.e., nutritional (e.g., vitamin C and lycopene content), physical (e.g., firmness, color, weight loss), microbial safety, and economic viability, is offered. The general objective is to advance adaptive, sustainable, and adaptable storage practices for mitigating tomato postharvest losses, particularly in resource-constrained settings where the costs are most significant.

Methodology

Strategies for literature search

This research was conducted to answer these questions;

Q1: What are the effective storage techniques for tomatoes?

Q2: How do storage methods influence the qualities of tomatoes?

This systematic review was written and revised to conform to the PRISMA guidelines, following the method outlined by Hopkins et al. (2021). Initially, the search timeframe was within 1999 to 2025, but was later limited to 2013–2025, to ensure the exclusion of obsolete information. Six keywords (Tomato storage, Postharvest quality, Modified atmosphere packaging, Evaporative cooling, Microbial spoilage, and tomato storage) were used in the search. The databases used were Scopus, PubMed, and Science Direct. Google Scholar was used in a specific search of some articles by author name and year.

Inclusion and exclusion criteria

The articles used in this review were required to meet the following criteria:

- Be written in English language and be a full written text,
- Be an original research study or a review work that fully explores tomato storage,
- Compare different storage techniques
- Be a peer-reviewed article; finally,
- Articles that answer the research question partially or completely were considered.

The exclusion criteria included:

- Abstracts and proceedings without full text;
- Articles that are not about tomato storage;
- Articles and works that used techniques that aren't generally possible worldwide;
- Articles in a non-English language.

Results

Search result

PubMed and article search engines (Scopus and Google Scholar) database were used for the literature search, of which 300 articles were identified. From this, 199 articles were identified as duplicates, and 101 articles were accepted and subjected to screening by abstracts, titles, and keywords. The screening process led to the exclusion of 68 records based on the earlier stated exclusion factors (Figure 1). The remaining 33 articles were identified for full-text reviews, of which 14 articles were also later excluded due to the following reasons: (i) No adequate information about the storage technique (n =4), (ii) the impact of the technique on the quality parameter was not stated (n =6), (iii) the full text was not accessible and locked (n =4)

Tomato quality parameters

The storage life, market value, nutritional status, and consumer acceptance of the tomato are controlled by

the quality before and after storage. Tomato is a climacteric fruit that undergoes postharvest physiological changes during ripening, and these play a vital role in its microbiological, physical, and nutritional status. According to El-Mesery et al. (2024), these metrics can be roughly divided into three categories: nutritional, physical, and microbiological qualities. Various storage techniques tend to have great impacts on these parameters. When tomatoes are subjected to any storage or preservation methods, these parameters provide information on how effective the storage or preservation method is.

Nutritional quality of tomatoes

Tomatoes are famous for their ascorbic acid (vitamin C) and lycopene nutritional value, being the key parameters affected during storage. Vitamin C is a very potent antioxidant that is crucial for the synthesis of collagen, metabolism of iron, and immunity (Carr & Maggini, 2017). It is very labile and sensitive to oxidative degradation in the presence of oxygen, light, and heat. Extreme losses can be realized even owing to brief periods of inadequate storage (Ayomide et al., 2019). For example, ambient storage promotes the degradation of vitamin C while refrigeration slows it down (Ayomide et al., 2019). Tomatoes may lose their vitamin C content between 30 to 50% even upon long-term storage at room temperature (El-Ishaq & Obirinakem, 2015; Bhandari & Lee, 2016) because of enzymatic and non-enzymatic oxidation.

Red carotenoid pigment lycopene, responsible for the characteristic red colour of tomatoes, is also an important determinant in inhibiting inflammation and oxidative stress. Temperature, oxygen, and light exposure, among others, control its stability. Storage and temperature predispose it to degradation, but, at times, light heat treatments have been reported to enhance bioavailability of lycopene via isomerization (Ilahy et al., 2019; Arballo et al., 2021). Well-regulated environmental and refrigeration conditions in controlled storage enhance the retention of lycopene content better than open or ambient storage (Singh et al., 2021). This implies that light exposure must be avoided, storage temperatures lowered, and oxygen exposure minimized to maintain these health compounds in a preserved state.

Microbial spoilage of tomatoes

Tomatoes tend to spoil faster, particularly when stored under suboptimal conditions, because they are susceptible to the growth of microbes due to their high water activity (a_w) and nutrient-dense nature, particularly their simple sugar content, organic acids, and vitamins. They are very perishable due to their vulnerability to spoilage, and microbial spoilage (Figure 2) is one of the major causes of postharvest losses worldwide, especially in the tropics and subtropics, where there is a lack of cold chain logistics infrastructure (Enyiukwu et al., 2020).

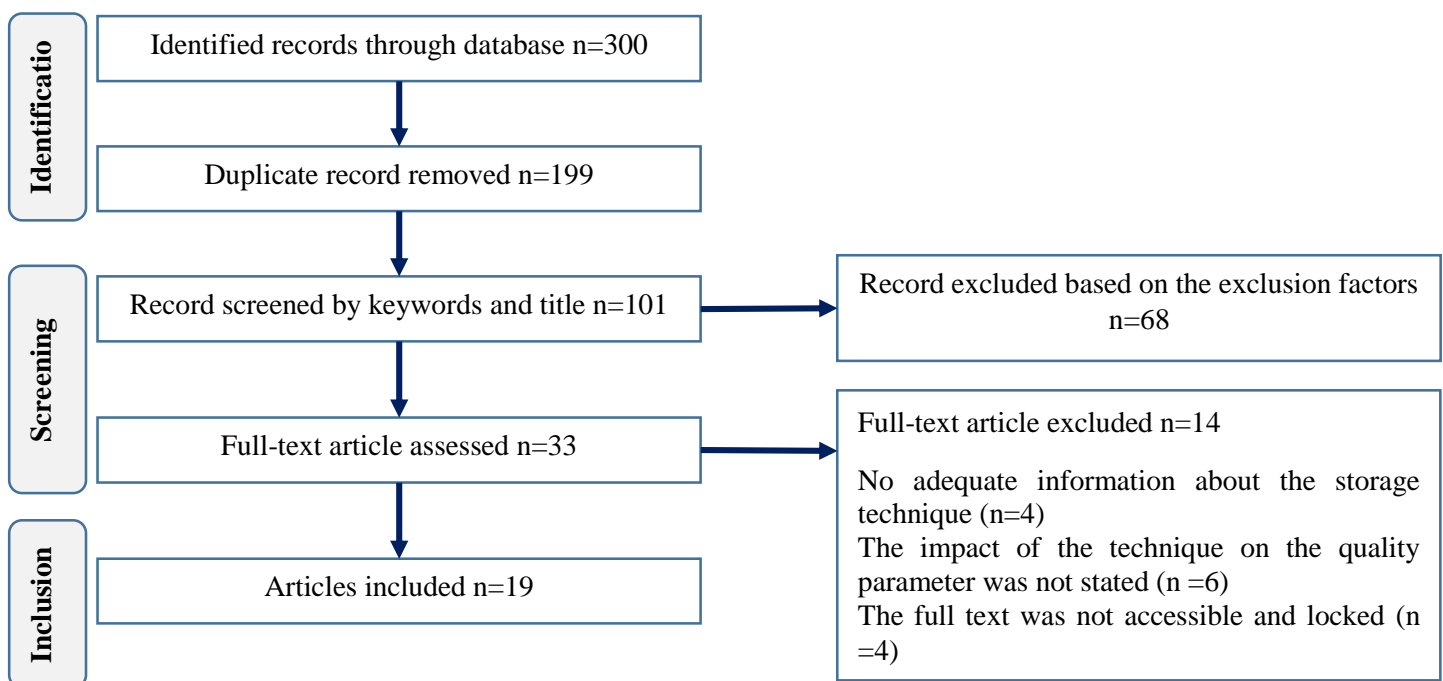


Figure 1: PRISMA flow diagram of literature search and screening of tomato storage techniques

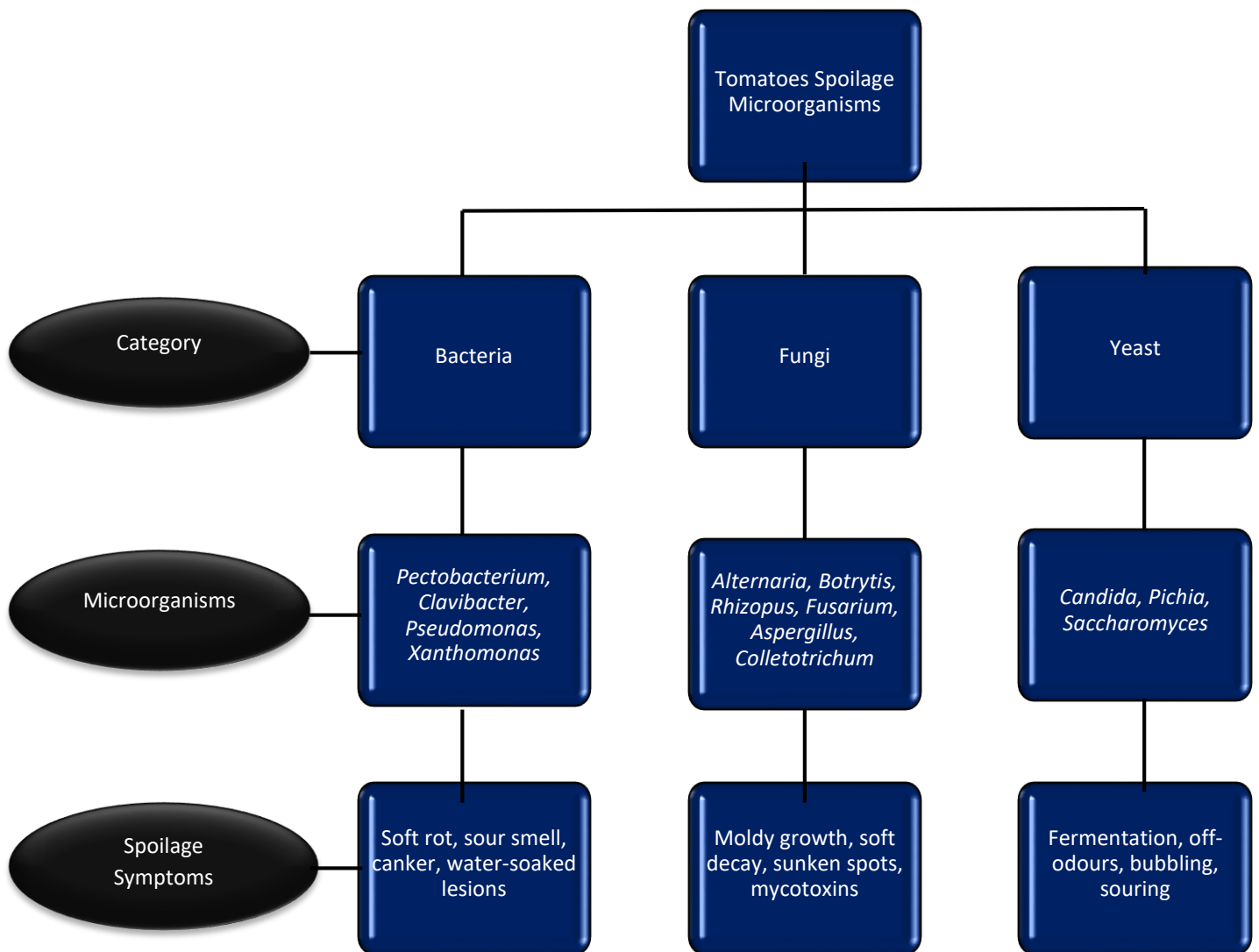


Figure 2: Lists of the various types of tomato rot, microbes, and their symptoms.

Fungal rot is the most prevalent and debilitating type of microbial breakdown. Invaders are often aggressive spoilage fungi like *Rhizopus stolonifer*, *Alternaria alternata*, and *Botrytis cinerea*. *Rhizopus* induces soft rot and liquefaction of the tissues, *Botrytis* induces gray mold and powdery mycelial growth on water-soaked tissue, and *Alternaria* induces black mold and sunken myxomycete-like lesions. When the tomatoes are injured, overripe, and stored at room temperature under high relative humidity with poor ventilation, the fungi do well (Beaulieu et al., 2022)). Fungal infection may also be worsened by unsatisfactory harvesting, mechanical injury sustained during handling, and the lack of sanitizing treatments.

Apart from fungus, diseases caused by bacteria are also essential factors in quality decline. Some of these bacteria are *Xanthomonas campestris*, which causes

bacterial spot, *Ectobacterium carotovorum*, which causes tissue maceration and rotten exudates, and *Pseudomonas spp.*, which is associated with a well-damp environments causing enzymatic cell wall disintegration and pitting of fruit surfaces. Strict cleanliness and control procedures are necessary since these bacteria not only decrease marketability but also pose health hazards if consumed (Nguetti, 2019; Ali et al., 2021).

Several preservation techniques are used in various value chains to reduce microbial spoilage. Since lower temperatures suppress metabolic rates and prevent microbial multiplication, cold storage is still one of the most successful therapies. By lowering oxygen levels while preserving humidity, modified atmosphere packaging (MAP), frequently used in conjunction with

fungistatic sheets, helps inhibit the growth of bacteria and fungi (McMillin, 2020).

Alternative low-cost techniques are becoming more popular in resource-constrained settings where refrigeration might not be practical. Through natural evaporative processes, evaporative cooling chambers constructed from locally accessible materials can reduce ambient temperatures by 10 to 15 °C, prolonging the shelf life of tomatoes by a few days (Manyozo et al., 2018).

In a similar vein, the antifungal and antibacterial qualities of natural antimicrobials such as neem leaf extract, garlic oil, vinegar sprays, and chitosan coatings are being investigated. Without compromising fruit quality or creating toxicological hazards, these environmentally benign and biodegradable therapies show potential in lowering microbial burdens.

Furthermore, new studies highlight how crucial it is to incorporate predictive modeling and microbial profiling into postharvest management procedures. It is feasible to customize interventions according to risk assessment and product susceptibility by thoroughly understanding the distinct microbial populations and spoilage processes during storage (Taiwo et al., 2024). In addition to improving food safety, these focused strategies help lower the startling postharvest loss rates, which in some developing nations can amount to as much as 40% for tomatoes alone (FAO, 2019).

Maintaining product quality, increasing shelf life, and guaranteeing food security depend on understanding efficient microbial management in tomato storage. The most sustainable action is a multifaceted approach that includes cold storage, appropriate handling, good postharvest hygiene, and combining traditional and innovative preservation techniques.

Common storage methods

One of the critical postharvest activities with direct impacts on tomatoes' shelf life, nutritional retention, and marketability is storage (Umeohia & Olapade, 2024). Being climacteric, not only do tomatoes continue to ripen, but they also continue to respire even after being harvested, rendering them highly prone to rapid deterioration if not stored properly (Ochida et al., 2019). In order to control these physiological processes, minimize postharvest losses, and maintain quality, a number of preservation methods have been devised. The degree of technology, cost, energy input, and applicability under varying conditions vary greatly among the methods, particularly for tropical and resource-limited conditions.

Ambient storage

Because of convenience, availability, and lack of energy requirement, ambient storage, typically 25 °C to 30 °C with tolerable humidity (Mahmood et al., 2019), remains the most prevalent mode of tomato storage in the developing world. Regrettably, it is also the least efficient technique in maintaining quality.

Tomatoes at room temperature are prone to microbial spoilage, nutritional loss, and quick physiological breakdown. The high temperature hastens the respiration rate, causing softening, shrinkage, and water loss. Lycopene also starts to deteriorate upon contact with oxygen and light, and vitamin C easily oxidizes at high temperatures (Chen et al., 2021).

In addition, ambient storage promotes the growth of microorganisms, especially spoilage fungi like *Alternaria*, *Rhizopus*, and *Botrytis* species (Zaman et al., 2025) that cause food spoilage a few days after harvest.

Due to its limitations, ambient storage is generally only considered appropriate for very short-term storage and where sale or consumption is imminent. Ambient storage, although cost-free, incurs high costs in terms of high spoilage and nutritional loss.

Refrigeration

Refrigeration is one of the most successful contemporary techniques of increasing tomatoes' shelf life and involves temperatures generally between 4 °C and 10 °C. Microbial metabolism and enzyme activity slow down considerably at low temperatures, postponing spoiling. Therefore, tomatoes kept in a refrigerator stay fresh longer than those kept at room temperature regarding firmness, colour, and nutrition (Ali et al., 2021).

As a result of decreased transpiration under refrigeration, weight loss is also significantly less. Tomatoes kept at room temperature had 15% weight loss, than 5% weight loss reported for the one refrigerated over the course of two weeks (Singh et al., 2021). Refrigeration is not without its disadvantages, especially for tropical cultivars. As they are chilling sensitive, tomatoes kept below 12 °C for longer periods of time develop symptoms of chilling injury, including:

- Pitting and sunken areas on the skin
- Uneven ripening or failure to ripen
- Off-flavors and loss of aroma
- Increased susceptibility to decay upon removal from cold storage

According to Biswas (2016), chilling injuries are more noticeable when tomatoes are picked before they are

entirely ripe or stored in cold conditions and then exposed to warm temperatures. Despite this, intermittent warming (sometimes called "rewarming") has been demonstrated to lessen the consequences of chilling injury.

Therefore, if temperature and humidity are appropriately managed, refrigeration offers good short- to medium-term storage within few weeks for partially ripened or ripe tomatoes (Pal et al., 2018). However, because of its expense and reliance on electricity, its use is restricted in off-grid or rural areas. According to James and James (2023), one of the main drawbacks is that chilling injury from refrigeration can alter texture, ripening, and flavor, particularly in delicate cultivars or when temperatures drop below the ideal range.

Evaporative cooling

Tomatoes can be economically and environmentally preserved via evaporative cooling, which is particularly useful in areas with poor electrical supply. The device uses the principle of water evaporation, which lowers the ambient temperature inside the storage chamber by absorbing latent heat from the surroundings as the water evaporates (Manyozo et al., 2018).

Evaporative cooling methods that are often used include:

- Zeer pots (pot-in-pot coolers)
- Charcoal coolers
- Evaporative cooling chambers (ECCs), which are made from brick, sand, and other porous materials

These systems are advantageous in hot, dry climates, where ambient conditions enhance the cooling effect. For tomatoes, evaporative cooling can:

- Lower storage temperature by 5–15 °C compared to ambient air (Anyanwu et al., 2021)
- Maintain high relative humidity (above 90%), which reduces water loss (Manyozo et al., 2018)
- Extend shelf life up to 12–14 days, depending on environmental conditions and tomato variety (Manyozo et al., 2018)

In contrast to tomatoes kept at room temperature, those kept in evaporative coolers maintained greater firmness, colour, vitamin C, and marketable look (Yusuf et al., 2025). This approach is a useful one for small-scale postharvest management since it also considerably delayed microbiological spoiling. It works well in rural locations, requires no energy to run, and is simple to construct. Despite these benefits, its application may be challenging because it needs to be

replenished with water frequently to remain effective, and it is less utilized in areas that are humid or wet.

Comparative analysis of storage methods

The various storage techniques highlighted in this work affect the quality parameters discussed earlier differently. These storage methods subject the tomato to certain conditions, which impact nutritional, physical, microbial, and economic parameters.

Nutrient retention

Preserving nutrients, particularly vitamin C and lycopene, is a significant indicator of storage effectiveness.

- It has been demonstrated that refrigeration considerably reduces the oxidative deterioration of vitamin C, especially when stored between 4 and 10 °C. According to recent research by Kabir et al. (2020) and Dodgson et al. (2023), cold storage retains lycopene stability in addition to ascorbic acid content. However, in tomato cultivars that are sensitive to chilling, extended exposure to low temperatures may hinder lycopene production, leading to blotchy colouration or uneven ripening.
- Modified Atmosphere Packaging (MAP) effectively reduces respiration rate and delays senescence, contributing to better retention of vitamin C and carotenoids. In a study by Sharma et al. (2023), MAP-treated tomatoes maintained over 85% of their initial lycopene content and exhibited minimal loss in ascorbic acid after 14–21 days of storage, depending on the cultivar and film permeability.
- Evaporative Cooling remains a viable low-cost method for maintaining nutritional quality, especially in off-grid or resource-limited settings. According to Lufu et al. (2025) and Manyozo et al. (2018), this method creates a microclimate with lower temperatures and elevated humidity that helps reduce oxidative stress, preserve antioxidants, and slow enzymatic degradation.
- Ambient Storage, in contrast, accelerates nutrient loss due to exposure to high temperature and fluctuating humidity. Majidi et al. (2014) found that vitamin C and lycopene concentrations drop rapidly under ambient conditions, with significant degradation observed within the first 3–5 days of storage.

Physical quality parameters of tomatoes during storage

The comparative effects of storage conditions on the quality parameters of tomatoes is presented in Table 1. Oliveira-Bouzas et al. (2021) demonstrated that both refrigeration and Modified Atmosphere Packaging (MAP) are effective in delaying softening, preserving firmness significantly better than ambient storage. Additionally, evaporative cooling, which operates under reduced temperature and high humidity conditions, also slows down firmness degradation by minimizing thermal and water stress on the fruit (Manyozo et al, 2018). Tomatoes stored at ambient temperatures soften quickly (Jung et al., 2019). Refrigeration and cold storage are effective at retaining firmness and reducing weight loss, but chilling injury may cause textural issues. Evaporative cooling maintains firmness better than ambient storage, though not as well as refrigeration. MAP maintains excellent firmness and appearance, but is costlier.

Another critical parameter is the colour change in tomatoes, especially during the development of red colour, which serves as a visual sign of ripeness and quality. It is worth noting that poor storage conditions, especially refrigeration below 10 °C, might prevent the

production of lycopene, which can lead to blotchy or uneven Colouration from chilling harm (Biswas et al, 2016). On the other hand, MAP successfully preserves visual quality by regulating oxygen levels, which lessens pigment oxidation and aids in maintaining a vivid red Colour over time (Caleb et al., 2013). Weight loss is another critical physical indicator, primarily driven by transpiration and respiration. These processes lead to moisture loss and softening, ultimately compromising fruit quality. Under ambient conditions, tomatoes can lose over 10% of their weight within just 5 to 7 days (Arah et al., 2016). Refrigeration mitigates this effect, often reducing weight loss to below 5% over the same period, provided the relative humidity (RH) is maintained above 90%. Evaporative cooling systems, such as pot-in-pot or charcoal coolers, are especially effective in tropical settings, where they maintain RH between 85–95% and offer substantial temperature reduction, thereby preserving moisture content (Manyozo et al., 2018). Similarly, MAP significantly limits both transpiration and respiration by creating a controlled gaseous environment, leading to minimal weight loss typically under 2–3% (Caleb et al., 2013).

Table 1: Quality Parameters of Tomatoes stored under different Storage Conditions

Storage Method	Firmness Retention	Weight Loss	Colour Stability	Authors/Source
Ambient Storage	Poor – Rapid softening due to enzymatic degradation and moisture loss	High (>10% within 5–7 days) due to uncontrolled RH and transpiration	Poor – Accelerated ripening and pigment degradation	Majidi et al., (2014); Dodgson et al. (2023)
Refrigeration (10 °C)	Good – Preserves tissue integrity and slows enzymatic breakdown	Low (<5%) with RH >90%	Medium – Risk of blotchy colouration below 10°C	Kabir et al. (2020);
Evaporative Cooling	Moderate – Reduced enzymatic activity in dry climates	Moderate (~5–7%) depending on humidity level	Moderate – Maintains red colour better than ambient	Manyozo et al. (2018); Lufu et al. (2025)
Modified Atmosphere Packaging (MAP)	Excellent – Inhibits softening via low O ₂ and CO ₂ control	Low (<3%) – Controlled gas exchange reduces respiration	Excellent – Lycopene preservation and reduced oxidative browning	Caleb et al. (2013); Sharma et al. (2023)
Cold Storage (4–5 °C)	Excellent – Optimal firmness maintenance with minimal enzymatic activity	Low (<3–4%) – Effective moisture control	Excellent – Maintains colour and prevents overripening	Opara & Mditshwa (2013); Singh et al. (2023)

Microbial spoilage

Microbial spoilage remains a critical concern in the postharvest handling of tomatoes due to their high

moisture content, thin skin, and nutrient-rich composition. Spoilage is predominantly caused by fungi such as *Botrytis cinerea*, *Alternaria spp.*, and

Rhizopus stolonifer, alongside various bacterial contaminants. The extent and nature of microbial proliferation vary significantly across different storage methods due to differences in temperature, relative humidity (RH), oxygen availability, and handling practices (Table 2).

Refrigeration

Refrigeration, typically maintained at 4–10 °C, substantially slows down microbial activity by suppressing respiration and enzymatic reactions.

Depending on tomato maturity and handling, this method delays spoilage for 1–2 weeks. However, it is not entirely foolproof; some psychrotrophic fungi, especially *Botrytis cinerea*, can still develop under refrigeration, particularly in conditions of excessive moisture or poor hygiene (Biswas et al, 2016). Moreover, fluctuating temperatures due to power outages or poor cold chain management can compromise the integrity of refrigerated storage, making it moderately effective under suboptimal conditions.

Table 2: Impact of the Storage Method on Microbial Activities and their Limitations

Storage method	Microbial spoilage risk	Dominant pathogens	Spoilage onset	Positive effects	Key limitations	Reference(s)
Ambient Storage	Very High	<i>Alternaria</i> spp., <i>Rhizopus</i> , <i>Fusarium</i>	2–4 days	No cost or infrastructure; useful for immediate local consumption	No control of temp/RH; high microbial growth rate	Arah et al. (2016)
Refrigeration	Low to Moderate	<i>Botrytis cinerea</i> , <i>Erwinia</i> spp.	7–14 days	Slows respiration and microbial growth; extends shelf life	Risk of chilling injury; psychrotrophs may survive	Biswas et al, (2016)
Evaporative Cooling	Moderate	<i>Fusarium</i> spp., surface molds	5–7 days	Reduces temperature using passive cooling; suitable for off-grid rural areas	Less effective in humid climates; water hygiene issue	Manyozo et al (2018); Lufu et al. (2025)
Modified Atmosphere (MAP)	Low	<i>Penicillium</i> , <i>Cladosporium</i>	14–21 days	Maintains colour, firmness, and nutrient retention via gas control	Requires packaging precision; anaerobic spoilage risk	Caleb et al. (2013); Sharma et al. (2023)
Cold Storage	Very Low	<i>Botrytis cinerea</i>	Up to 3 weeks	Longest shelf-life extension; effective for large-scale storage with high humidity	Infrastructure cost, energy demands	Opara & Mditshwa (2013); Singh et al. (2023); Taiwo et al. (2024)

Evaporative cooling

Evaporative coolers, such as charcoal or clay pot systems, use water evaporation to reduce storage temperature by 5–15 °C below ambient levels (FAO, 2012). This creates a relatively calm and humid environment, which delays moisture loss and microbial spoilage in arid climates. Studies have shown that evaporative cooling can extend tomato shelf life by 5–7 days compared to ambient storage,

primarily by suppressing the growth rate of spoilage fungi (Manyozo et al, 2018).

However, in humid environments, where evaporative cooling efficiency declines, the risk of microbial contamination can remain high due to persistently elevated RH. Additionally, hygiene in cooler construction and water quality is essential, as contaminated water or surfaces can introduce spoilage organisms.

Modified atmosphere packaging (MAP)

MAP involves sealing tomatoes in films that modify the internal gas composition, typically reducing oxygen levels and elevating carbon dioxide concentrations. These atmospheric changes suppress aerobic microbial growth and slow fruit respiration. Studies have reported a significant reduction in microbial spoilage using MAP, with shelf life extended up to 2–3 weeks (Caleb et al., 2013). High CO₂ concentrations inhibit the growth of fungi like *Penicillium* and *Cladosporium*, and also suppress bacterial activity. However, MAP's effectiveness is contingent on correct packaging material selection and gas balance; if oxygen levels become too low, anaerobic pathogens may thrive, causing off-flavors and internal breakdown

Cold storage

Cold storage, especially with controlled humidity and 0–10 °C temperatures, is the most effective means of preventing microbial spoilage (Zhao, 2021). Both pathogen growth and loss of moisture are limited by the low temperature and high RH combination. Cold storage, with good control, can reduce microbial spoilage by over 70%, rendering tomatoes marketable for a period of up to 3 weeks (Opara & Mditshwa, 2013; Singh et al., 2023). However, in ideal circumstances, *Botrytis cinerea* and other cold-hardy species are capable of living. In addition, infrastructure constraints and energy consumption limit its availability, particularly in rural villages of developing countries.

Cost and Feasibility of the Tomato Storage Methods

Economic feasibility and technical appropriateness of tomato storage methods are paramount to reducing postharvest losses, particularly in low- and middle-income countries where losses are greater than 40% (FAO, 2019). As a tomato is a perishable produce, effective storage methods must meet preservation quality, cost, and the availability of infrastructure. The conventional storage techniques: ambient storage, cold stores, evaporative cooling, refrigeration, and modified atmosphere packing (MAP), have different impacts on the storage-ability of tomatoes based on their feasibility with their viability in relation to field realities.

Ambient storage is the most prevalent practice, especially among rural and peri-urban small-scale farmers. It is typically achieved by placing harvested tomatoes in trays, baskets, or sacks in shade and at room temperature. Though its cost is nearing zero and its infrastructure is negligible, ambient storage exposes

tomatoes to rapid loss of quality through elevated temperatures and humidity. Spoilage will develop in the period 2 to 4 days when microbial growth accelerates (Arah et al., 2016). Though more convenient than any form of storage, ambient storage is technologically inefficient for the maintenance of postharvest quality and is best applicable only to short-term holding or immediate marketing.

Refrigeration is technologically advanced and can slow respiration rates, enzymatic browning, and microbial spoilage. Storage in the 4–10 °C range has been reported to enhance shelf life up to two weeks while retaining visual and nutritional qualities (Kouassi et al., 2021). But the economic worth is much higher. Refrigeration machinery entails a very high initial capital outlay as well as recurrent costs in terms of electricity and maintenance. These costs represent a major adoption hurdle in places where energy infrastructure is unreliable or not feasible to reach. Additionally, its viability is limited in off-grid areas unless powered by alternative energy solutions like solar refrigeration. As such, refrigeration is more applicable in commercial farming setups, cooperatives, or urban supply chains with reliable utilities.

Evaporative cooling presents a low-cost and environmentally friendly alternative, especially in arid and semi-arid zones. Systems such as clay pot coolers and charcoal-based coolers harness the natural principle of water evaporation to reduce temperature and maintain humidity, thereby slowing microbial proliferation. Studies show that evaporative coolers can reduce internal temperatures by 10–15 °C below ambient conditions and preserve tomato freshness for up to 10 days (Yusuf et al., 2025). Construction costs are minimal, usually between \$10–\$50, and materials are locally available. Importantly, no electricity is required. While its effectiveness can vary based on ambient humidity and airflow, evaporative cooling is highly feasible for small-holder farmers lacking refrigeration access.

Modified atmosphere packaging (MAP) employs specialized packaging films to modify the internal gas composition by lowering oxygen levels and increasing carbon dioxide. This alteration inhibits microbial growth and delays ripening processes. MAP can extend tomato shelf life to 2–3 weeks and significantly preserve firmness, flavor, and nutritional content (Caleb et al., 2013; Khalid et al., 2024). However, MAP requires packaging equipment, gas mixtures, and sealing technology, which are moderately or highly costly. The complexity of using and maintaining the

packaging environment makes it more suitable for medium-to-large operations, particularly those involved in export or long-distance supply chains. While technically promising, its adoption among small-holder farmers remains limited due to cost, technological barriers, and lack of awareness or training.

Cold storage facilities, representing large-scale refrigeration infrastructure, are the most advanced among all methods. These facilities maintain constant low temperatures and relative humidity, supporting long-term storage and inventory control across the supply chain. When integrated with pre-cooling and proper handling, cold storage can extend tomato shelf life to 3–4 weeks with minimal quality loss (Opara & Mditshwa, 2013; Firdous et al., 2025). However, the capital investment is steep, coupled with ongoing costs related to electricity, maintenance, and trained personnel (Oluwalana et al., 2020). Infrastructure requirements are substantial, including insulation materials, backup generators, and monitoring systems. Consequently, cold storage is typically viable only for commercial enterprises or through public-private partnerships supporting cooperative use. Efforts to introduce solar-powered cold rooms and modular cold chain units are emerging to bridge this feasibility gap. Across all methods, trade-offs between cost, quality retention, and infrastructure must be weighed carefully. Technologies like evaporative cooling offer a pragmatic bridge for small-holder farmers, while refrigeration, MAP, and cold storage are more appropriate for larger-scale operations. Developing decentralized storage solutions and promoting low-cost innovations can help democratize access to postharvest technologies and reduce food losses significantly.

Recent advancements in postharvest management complementing the storage of tomatoes

In the face of mounting global food insecurity and substantial postharvest losses, especially in perishable crops like tomatoes, there has been a progressive shift toward integrating advanced, technology-driven solutions into traditional postharvest management systems (Table 3). Emerging developments in the fields of the Internet of Things (IoT), predictive microbial modeling, and metabolomics are not stand-alone technologies but rather complementary tools that can be utilized to optimize the current tomato storage methods, such as refrigeration, cold chain logistics, evaporative cooling, and Modified Atmosphere Packaging (MAP).

Among the most significant technological advances has been the integration of IoT-based cold chain monitoring systems. Arduino microcontroller-embedded and ESP32 Wi-Fi module-enabled devices provide round-the-clock tracking and automatic control of temperature and relative humidity during storage and distribution (Narayana et al., 2024). In tomato storage, where even minimal temperature fluctuations can accelerate respiration rates and microbial spoilage, these IoT systems offer real-time insight into data and alerts that allow handlers to take corrective action straight away. For instance, Manonmani et al. (2024) used controller PID to operate IOT, when tomatoes were stored at temperatures of (32–35.5 °C) and with the humidity (65–85%). Meanwhile, Proportional-Integral-Derivative (PID) controller, a widely used automated control system that continuously adjusts a system's output based on the error between a setpoint and a measured process variable (Doroshenko, 2017). Shankaraswamy and Radhika's (2024) study demonstrated that IoT application in refrigerated storage achieved noticeable quality loss and microbial contamination reductions during tomato storage ultimately increase shelf life and reduce waste. The adoption of IoT in tomato storage is not limited to temperature and humidity adjustments. Dash et al. (2022) reported the use of this technology in for the regulation of pH and TTA (chemical spoilage parameters) in tomato storage. It was observed by the authors that IoT based storage stored the tomatoes for 12 days with minimal spoilage, whereas, the normal storage lasted for just 6 days.

In addition to physical monitoring, predictive modeling software is increasingly used to anticipate spoilage hazards. The Postharvest Supply Chain Microbial Traveler (PSCMT) model, a simulation system that traces and predicts microbial flow along the supply chain, has shown exceptional promise in identifying microbial entry and growth hotspots from farm to retail (Zoellner et al., 2018). By incorporating variables such as ambient temperature, humidity, and handling time, the models allow stakeholders to introduce interventions at precise critical control points, thus reducing microbial load and the occurrence of spoilage in tomatoes. Although a more subtle model like the log-linear regression model (Qange et al., 2024) exist, their functionality is nothing compared to PSCMT. This is because log-linear regression model is a statistical technique that analyses the relationships between variables (Bakeman & Robinson, 2013), while PSCMT model mechanistic

dynamic model used for simulation and visualizing microbial contamination (Zoellner, 2017). PSCMT combined with good packaging and handling practices, such predictive models can streamline operations and reduce postharvest inefficiencies.

Furthermore, the application of metabolomic profiling methods, including mass spectrometry (MS) and nuclear magnetic resonance (NMR), is changing the way new tomato ripening and spoilage pathways are discovered. The methods allow scientists and storage managers to monitor some metabolites, such as lycopene, sugars, organic acids, and volatiles that determine freshness and quality. Metabolomic evaluation of postharvest tomato storage, as described by Firdous et al. (2025), provided useful data regarding the quality-related compounds degradations. This type of information can be utilized to maximize storage procedures, including changing exposure to oxygen or ethylene in MAP systems, to prevent loss of flavor, nutritional value, and shelf life.

Collectively, these technologies are powerful augmentations to conventional methods of tomato storage. Providing immediate environmental feedback, anticipating trends toward spoilage, and specifying

quality at the molecular level, they offer an integrated system for precision postharvest management. Although their deployment in low-resource settings remains challenging in terms of cost and technicality, ongoing innovations in low-cost sensors, open-source modeling frameworks, and mobile diagnostic technology make such technology more accessible. Their convergence holds great potential to arrest the estimated 40% postharvest loss rate for tomatoes, especially in developing nations (FAO, 2019), and to provide more secure, higher-quality produce to reach consumers' hands (Taiwo et al., 2024).

As presented in Table 3, AI-based and handling enhance the quality parameters of tomatoes and farm produce. The techniques involve using a deep learning algorithm to recognize patterns through previous data, process and predict the best handling conditions for farm produce and, contextually, tomato. Further to the work of Islam & Hatou (2024), reported in Table 3, Yu et al. (2025) showed through the integration of AI technology that safety practices improve traditional risk management and help proactively identify and reduce potential hazards in food.

Table 3: Recent storage complementary advancements in postharvest management of tomatoes

Storage Method	Technology Employed	Predictive Modeling Tool	Conclusion and Recommendation	Source/Author
Cold Chain with IoT Integration	IoT sensors, Arduino microcontrollers, and ESP32 modules integrated into refrigeration units	Machine Learning models (e.g., Polynomial regression)	Implementing IoT-based monitoring systems can optimize storage conditions, enhance shelf life, and reduce postharvest losses in tomatoes.	(Narayana et al.,2024); Shankaraswamy & Radhika (2024)
Farm-to-Retail Supply Chain	Simulation frameworks for pathogen tracking	PSCMT (Postharvest Supply Chain Microbial Traveler) model	Simulation tools can identify critical points in the tomato supply chain to mitigate microbial contamination risks.	Zoellner et al. (2018)
Postharvest Metabolomics	Mass spectrometry (MS), Nuclear Magnetic Resonance (NMR) spectroscopy	Metabolomic profiling	Metabolomic approaches can inform targeted interventions to prolong shelf life and maintain tomato quality by understanding biochemical changes during storage.	Firdous et al. (2025)
Smart Packaging Systems	Intelligent indicators, RFID, gas sensors	Decision Support Systems (DSS)	Smart Modified Atmosphere Packaging (MAP) offers dynamic feedback on gas balance and product condition in real-time, enhancing tomato shelf life and quality.	Khalid et al. (2024)
AI-Based Handling and Sorting	Computer vision, AI camera, AI classifiers, machine learning algorithms	Quality prediction and shelf-life scoring	AI-driven sorting reduces damage and ensures quality before storage, improving overall storage efficiency and	Islam & Hatou (2024); Okabe et al. (2025)

Future prospects

The future of tomato postharvest storage is synergy between traditional storage and cutting-edge technological interventions. While techniques such as ambient storage, refrigeration, evaporative cooling, modified atmosphere packaging (MAP), and cold storage have provided varying degrees of success in preserving quality, the future looks at enhancing their efficiency, scalability, and applicability, especially in the face of climate variability, population growth, and food security.

In future years, more emphasis will be placed on innovative postharvest technologies, including the Internet of Things (IoT), machine learning, and predictive modeling for real-time monitoring and controlling storage conditions. For instance, low-cost IoT sensors can be installed in rural cold chains to monitor temperature and humidity, alerting users to deviations that cause spoilage. These technologies are not just prospective for large-scale industrial use but are also increasingly becoming feasible for small-holder farmers from developing countries in miniaturized and inexpensive forms (Shankaraswamy & Radhika, 2024).

In addition, metabolomic and microbial profiling strategies will augment understanding of the biochemical and microbial modification that happens to tomatoes when stored. This will enhance personalized storage protocols optimized for cultivar-specific degradation profiles, regional climatic regimes, and market delivery schedules (Firdous et al., 2025). Personalised storage strategies will contribute significantly to curbing the current postharvest losses of 40% experienced in the majority of low-income countries (FAO, 2019). Another promising field includes the development of hybrid storage systems, such as solar-powered evaporative coolers in conjunction with MAP technologies, to address energy and packaging limitations at the same time. The utilization of biodegradable intelligent packaging materials impregnated with freshness markers or antimicrobial agents is also expanding and potentially further revolutionize tomato storage and transport (Khalid et al., 2024). For these innovations to be useful practically, policy support, infrastructure development, and farmers' education must change in tandem. Public-private partnerships and government initiatives can bridge the gap between research and implementation, especially for rural agricultural

societies where most of the tomato losses are being observed.

Conclusion

Tomatoes are a highly perishable fruit that has to be treated carefully upon harvesting to prevent loss of quality, which results in economic losses. The work has established that the storage method plays an essential role in the quality of tomatoes in terms of nutritional, physical, and microbial levels. Although refrigeration, cold storage, and MAP are superior preservation systems, they are costly and technically complex, which makes them unattractive for rural regions. Evaporative cooling is an inexpensive, locally available option of moderate performance. Ambient storage, although prevalent, is the least effective and contributes to maximum postharvest losses. The effective combination of advanced recent technology could help enhance tomato quality retention by effective tracking and prevention of microbial and biochemical activities

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