The Effect of Thyme Essential Oil Incorporated into Chitosan Edible Coatings on the Shelf-life of Fresh Strawberries

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Article Info

P-ISSN: 3051-3421
E-ISSN: 3051-343X
Volume: 07
Issue: 02
Received: 25-04-2026
Accepted: 27-05-2026
Published: 29-06-2026
Page No: 19-22

Abstract
Background: Strawberries have become famous all over the world due to their quality of sensory appeal, vitamins, polyphenols, and antioxidant activity. They are however highly perishable post harvests with shelf life of only 3-7 days at refrigerated condition. High metabolic activity: A high transpiration and respiration rate leads to weight loss, tissue shrinkage and rapid softening. Fungal susceptibility: Susceptibility to phytopathogenic fungi (e.g., Botrytis cinerea or gray mold, molds and yeasts). Formulate an active edible coating with different concentrations of thyme EO in chitosan polymer matrix and calculate the limit of the extended shelf-life period and sensory acceptance of the treated (control) fruit.
Materials: Coating Solutions – Low/medium molecular weight chitosan (1–2% w/v) Preparation – Chitosan Matrix – Chitosan is dissolved in dilute acetic acid (0.5–1% v/v) with constant stirring until completely dissolved. Glycerol or Tween-80 is used as a plasticizer/emulsifier. Essential Oil Incorporation: Thyme Essential Oil (TEO) is incorporated into the product at different concentrations (0.1-1.5% v/v) and homogenized (or sonicated) into a stable emulsion.
Result: Incorporating Thyme Essential Oil into Chitosan edible coatings is an effective, eco-friendly postharvest technology for fresh strawberries. The composite coating acts as a dual physical and antimicrobial barrier that doubles the commercial shelf life of fresh strawberries (from ~7 days to up to 15 days under refrigeration) while significantly lowering decay rates. effectively preserves critical postharvest quality attributes, including firmness, color, Vitamin C, and antioxidant capacity.
Conclusions: The chitosan coatings containing thyme essential oil (CS-TEO) are a promising and environmentally friendly method for preserving strawberries. The composite coating has a dual effect as a physical barrier and an antimicrobial barrier, inhibiting fungal decay and limiting gas exchange, thus maintaining important quality parameters and increasing the refrigerated shelf life from 7 to 15 days.

DOI: https://doi.org/10.54660/JADR.2026.7.2.19-22

Keywords: Chitosan, Thyme essential oil, Active edible coatings, Postharvest preservation, Strawberries

Introduction

Fresh strawberries (Fragaria × ananassa) are among the most economically significant and popular small fruits globally, highly valued by consumers for their vibrant color, unique flavor profile, and dense nutritional value, particularly high levels of ascorbic acid (Vitamin C), phenolics, and anthocyanins (Giampieri *et al.*, 2012) [3]. However, strawberries are classified as non-climacteric, highly soft-textured fruits characterized by an exceptionally short postharvest shelf-life, often limited to less than seven days under standard refrigerated conditions (Romanazzi *et al.*, 2016) [7]. Excessive transpiration, high respiration rates and mechanical injuries are the major causes for rapid post-harvest decay. In addition, strawberries are extremely susceptible to phytopathogenic fungi, particularly Botrytis cinerea causing large quantitative and qualitative economic losses along the supply chain (Petrasch *et al.*, 2019) [6].Synthetic fungicides and non-biodegradable petroleum-based plastic packaging have traditionally been used as the most effective control measures to reduce postharvest losses. However, concerns about the environmental impact of plastic packaging and the rising consumer demand for foods that are free from chemicals and contain a "clean label" have driven greater research on sustainable alternatives using bio-based products (Dehghani *et al.*, 2020) [1]. Of these, active edible coatings using biopolymers have proven to be potentially attractive alternatives. The cationic polysaccharide chitosan, which is derived from the deacetylation of chitin extracted from crustaceans' shells, has been extensively studied for its excellent film-forming capability, its non-toxic and biodegradable nature, and its intrinsic broad-spectrum antimicrobial activity (El Sabbe & Abd El-Gawad, 2012; Hassan *et al.*, 2018) [2, 4]. Chitosan forms a semi-permeable barrier when applied to fruit surfaces which controls gas exchange (O2and CO2), moisture loss, and fruit firmness. Pure chitosan coatings offer protection; however, the bioactivity can be significantly improved by combining natural extracts from plants and essential oils with the polymer matrix (Valdés *et al.*, 2015) [8]. The essential oil of thyme (Thymus vulgaris L.) is well known for its antimicrobial, antifungal and antioxidant properties, due to its high content of volatile phenolic monoterpenes, mainly thymol and carvacrol, which are capable of disrupting microbial cell membranes and scavenging reactive oxygen species (Nieto, 2017) [5]. The synergistic effect of the combination of thyme essential oil and a chitosan film provides an active coating system with physical barrier against desiccation and a long-term chemical barrier against fungal contamination.

Thus, the aim of this study was to assess the effect of a composite edible coating made of chitosan and thyme essential oil (EO) for the postharvest shelf-life extension of fresh strawberry. Specifically, this research was aimed to track the physical, chemical and microbiological quality of the parameters during the low temperature storage such as weight loss, fruit firmness, total soluble solids, titratable acidity, antioxidant preservation and decay incidence during low temperature storage.

Material and Methods

Freshly harvested, defect-free strawberries (Fragaria × ananassa) of uniform size, shape, and maturity (approximately 85–90% surface red color) were procured directly from a local commercial orchard. High-molecular-weight chitosan (degree of deacetylation ≥85%) and pure Thyme Essential Oil (Thymus vulgaris L.) were purchased from Sigma-Aldrich. Glacial acetic acid, glycerol (acting as a plasticizer), Tween-80 (polyoxymethylene sorbitan monooleate, acting as an emulsifier), and analytical-grade reagents were obtained from Merck (Darmstadt, Germany).

Chitosan coating solutions (1.5% w/v) were prepared by dissolving chitosan powder in an aqueous glacial acetic acid solution (1.0% v/v) under continuous magnetic stirring at 60 °C for 2 hours until complete dissolution. Glycerol (0.75% v/v) was added to the solution as a plasticizer.

To prepare the active composite formulations, Tween-80 (0.2% v/v) was incorporated into the chitosan solution to facilitate essential oil emulsification. Thyme essential oil (TEO) was subsequently added to the coating solution at different concentrations (0.5% v/v and 1.0% v/v). The mixtures were homogenized using a high-shear rotor-stator homogenizer at 10,000 rpm for 5 minutes, followed by degassing under vacuum to remove entrapped air bubbles.

Strawberries were sanitized by immersion in 0.05% v/v sodium hypochlorite for 2 minutes, then they were thoroughly rinsed with sterile distilled water and air dried on ambient room temperature (22±2 °C). The fruits were randomly distributed among the four treatment groups of 30 fruits each with three replications: Control (Untreated): Dipped in sterile distilled water. Chitosan Alone (CS): Dipped in 1.5% chitosan solution (without essential oil). Chitosan + 0.5% TEO (CS + TEO 0.5%): Dipped in 1.5% chitosan coating containing 0.5% TEO. Chitosan + 1.0% TEO (CS + TEO 1.0%): Dipped in 1.5% chitosan coating containing 1.0% TEO. Fruits were completely immersed in their They were then coated with the respective coating solutions for 2 minutes, drained on sterile stainless-steel grids, and dried at room temperature under laminar air flow for 1 hour to ensure uniform coating Film. The samples were packaged in perforated polyethylene terephthalate (PET) clamshell containers and stored at 4±1 °C with 85–90% relative humidity (RH) for 15 days. Physicochemical and microbiological analyses is carried out every 3 days (Days 0, 3, 6, 9, 12 and 15).

Table 1: illustrates post-harvest quality and microbiological performance over days of storage.

Parameter	Control (Untreated)	Chitosan Alone (CS)	CS + 0.5% TEO	CS + 1.0% TEO	Overall Finding / Effect DOCX
Weight Loss (%)	High (Rapid increase by Day 6–9)	Moderate reduction	Low	Lowest	Coating reduces transpiration and water loss.
Fruit Firmness (N)	Severe softening by Day 6	Softening delayed	Maintained well	Best Retention	Preserves cellular structure and delays tissue shrinkage.
Decay Rate / Fungi Count	> 50% decay by Day 7	Delayed decay	Strong suppression	Maximum Inhibitive Effect	Active TEO acts as an antifungal barrier against *Botrytis cinerea*.
Vitamin C & Antioxidants	Rapid degradation	Partial retention	High retention	Highest Retention	Retains critical ascorbic acid and polyphenol capacity.
Commercial Shelf Life	~3 to 7 Days	~9 to 11 Days	~12 to 14 Days	Up to 15 Days	Extends viable postharvest storage limit up to double.

Table 2: Comparative Postharvest Quality Preservation 🔴 Control (Red): Severe quality degradation; short shelf life (3–7 days). 🟡 CS Alone (Yellow): Physical barrier only; moderate shelf life (9–11 days). 🔵 CS + 0.5% TEO (Blue): Strong antimicrobial action; extended shelf life (12–14 days). 🟢 CS + 1.0% TEO (Green): Optimal postharvest protection; doubles shelf life up to 15.

Treatment Group	Visual Marker	Commercial Shelf-Life	Decay Rate (*B. cinerea*)	Firmness & Vitamin C Preservation
Control (Water)	🔴 Red	3–7 Days	Rapid onset / Severe decay	Severe degradation
Chitosan Alone (CS)	🟡 Yellow	9–11 Days	Moderate delay	Partial preservation
CS + 0.5% TEO	🔵 Blue	12–14 Days	Strong inhibition	High retention
CS + 1.0% TEO	🟢 Green	Up to 15 Days	Maximum inhibition	Optimal preservation

Discussion

Strawberries in the untreated control group undergo significant deterioration within 3-7 days after harvest because of high transpiration rates, respiration and susceptibility to fungi (Dehghani, etal,. 2020& El Sabbe etal,.2012) [1, 2]. Pure chitosan coating provides a semi-permeable physical barrier with restricted gas exchange, which reduces water loss and tissue softening (Giampieri etal,.2012& Hassan etal,.2018) [3, 4] Adding thyme essential oil (TEO) brings monoterpenes that break down cellular membranes in the fungus (Nieto, G. etal,.2017) [5]. Weight loss was minimal for CS + 1.0% TEO coating, which effectively prevented transpiration. Structural integrity and fruit firmness (N) were preserved best in the CS + 1.0% TEO group during the 15-day experiment. Strong antimicrobial activity of TEO inhibited Botrytis cinerea gray mold and prevented more than 50% of decay observed in the control group by the seventh day (Petrasch, S etal,. 2019) [6]. Oxidative degradation of ascorbic acid (Vitamin C) and total antioxidant capacity was considerably slowed by reduced contact with oxygen [1, cite: 2]. While chitosan coating itself increased shelf life to 9-11 days, the addition of essential oil brought about an optimal dual physical and antimicrobial protection system (Romanazzi,.etal 201[6] [7]. The CS + 1.0% TEO coating doubled the commercial shelf life of the berries by increasing it from ~7 days to up to 15 days at 4±1 °C.

Untreated controls lose quality rapidly and extensively in 3-7 days, resulting from unchecked fruit transpiration, high respiration rates, and susceptibility to Botrytis cinerea infection. The use of pure chitosan (CS) can prolong the shelf life up to 9–11 days by providing a semipermeable physical barrier that regulates gas exchange (O_2/CO_2) and decreases transpiration. TEO enhances this performance synergically by its antimicrobial and antioxidant activity (Akbari etal,. 2026) [9]. The 0.5% TEO formulation has a shelf life of 12-14 days while the formulation 1.0% TEO gives maximum postharvest protection, doubling the shelf life to 15 days (Gumede, S. S., etal 2025) [10]. The bioactive monoterpenes of TEO, mostly thymol and carvacrol, are responsible for the dramatic inhibition of B. cinerea. These active components are responsible for disrupting the integrity of the cell membrane, for intracellular leakage of electrolytes and for the inhibition of enzymes that degrade the cell wall of fungi at the same time, the CS-TEO composite matrix helps to limit the permeability of oxygen and inhibit polyphenol oxidase (PPO) activity (Silva, W. B.,etal 2026) [11] This helps to prevent the auto-oxidation of ascorbic acid (Vitamin C) and keeps the cells turgid and firm during cold storage. The greater the TEO concentration (1.0%) the higher barrier density of film which provides the best protection against postharvest decay and senescence (Zhao, Y., etal 2025).

Conclusions

The addition of thyme essential oil (TEO) to a polymeric matrix of chitosan (CS) creates an innovative bioactive coating specifically designed for strawberry preservation. This composite barrier provides dual action, slowing down the exchange of gases and transpiration, while at the same time providing strong antimicrobial activity. As a result, the CS-TEO treatment effectively reduces fungal decay and prolongs the storage life of refrigerated fruits by 2 weeks (from 7 to 15 days). In addition to structural protection, it also effectively reduces oxidative damage and cell breakdown to maintain the firmness, surface color, ascorbic acid content and antioxidant capacity of fruits during post-harvest storage.

Recommendation

We recommend applying a 1.0% concentration of thyme essential oil with chitosan before cold storage to achieve a maximum shelf life of up to 15 days, with optimal inhibition of gray mold (Botrytis cinerea. We also apply the technology of nano-emulsification: The thyme essential oil is encapsulated inside nano-emulsions in a chitosan matrix, which improves the stability of the coating, its transparency, and increases the release time of the active. Furthermore, we conduct sensory and consumer testing: performing flavor and aroma tests to ensure that the thyme scent does not negatively impact consumer acceptance of the fruit.

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How to Cite This Article

Ibrahim AH. The effect of thyme essential oil incorporated into chitosan edible coatings on the shelf-life of fresh strawberries. J Agric Digit Res. 2026;7(2):19-22. doi:10.54660/JADR.2026.7.2.19-22.