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Development and Evaluation of Zein and Triphala Edible Coatings for Postharvest Preservation of Tomatoes

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Abstract

The rapid perishability of tomatoes due to moisture loss, microbial spoilage, and oxidative degradation poses several challenges to postharvest handling and shelf-life extension. This study investigates the efficacy of protein-based edible coatings composed of zein and triphala extract in preserving the quality and extending the shelf life of fresh tomatoes under ambient storage 26 ± 1°C. Zein and triphala composite coatings ZT5 and ZT10 were developed and applied via dip coating. The physicochemical, microbial, antioxidant, structural, and sensory parameters of coated and uncoated tomatoes were evaluated over 45 days. Tomatoes coated with zein and triphala exhibited superior performance across all quality attributes, including reduced physiological weight and moisture loss, delayed increase in pH and total soluble solids, better retention of titratable acidity and firmness, and enhanced lycopene content. Microbial analyses showed markedly lower total plate counts and yeast and mold growth, between zein and triphala, contributing to coating stability and functionality. Sensory evaluation showed that ZT5-coated tomatoes retained high scores for appearance, texture, flavor, and overall acceptability up to Day 22, compared to Day 15 in control samples. These findings underscore the potential of zein and triphala edible coatings as an effective, natural, and biodegradable strategy for extending the shelf life and quality of tomatoes during postharvest storage.

Keywords:

- Zein
- Edible coatings
- Triphala
- Tomato

1. Introduction

Fruits and vegetables constitute a vital segment of global horticultural production, supplying essential nutrients and contributing to agricultural economies. However, their high perishability results in substantial postharvest losses, particularly in developing nations like India, which ranks second globally in fruit and vegetable production Horticultural Statistics at a Glance, 2018. These losses affect supply chains, market availability, and consumer access, underscoring the urgent need for efficient and sustainable preservation strategies Mason-D'Croz et al., 2019. Packaging technologies such as modified atmosphere packaging MAP, controlled atmosphere packaging CAP, vacuum packaging, and active packaging have shown efficacy in extending the shelf life of produce by regulating respiration and inhibiting microbial activity (Kader, 2002; Sandhya, 2010; Kader, 2003; Lopez-Rubio et al., 2004). However, their application is often hindered by high costs, technical complexity, and environmental concerns related to plastic waste (Arvanitoyannis & Bosnea, 2004; Yam et al., 2005). Intelligent packaging, while technologically advanced, remains largely inaccessible to small-scale producers due to economic and infrastructural limitations. In this context, edible coatings have gained prominence as an eco-friendly, cost-effective alternative. Composed of biodegradable materials like polysaccharides, proteins, and lipids, these coatings act as semi-permeable barriers to gases and moisture, reducing respiration and microbial spoilage (Baldwin et al., 1995; Debeaufort et al., 1998). When enriched with natural antimicrobials and antioxidants, they not only delay ripening but also enhance the nutritional and sensory quality of fruits and vegetables (Dhall, 2013; Duarte et al., 2015). Among coating materials, zein a maize-derived hydrophobic protein exhibits excellent film-forming properties, water vapor resistance, and mechanical strength, making it highly suitable for postharvest applications Bayer, 2021. Structured edible coatings offer improved barrier, mechanical, and bioactive properties, enabling more effective preservation of fresh produce (Silvestre et al., 2011; Bhatti et al., 2022). Surfactants like Tween-20 are often incorporated to stabilize formulations, reduce particle size, and improve dispersion of bioactive agents (Fathi et al., 2012; Patel et al., 2010). Additionally, herbal additives such as triphala an ayurvedic formulation containing Amalaki, Haritaki, and Bibhitaki offers potent antimicrobial and antioxidant activity, further enhancing the protective effects of coatings (Baliga et al., 2012; Sharma et al., 2020). Triphala is a well-known Ayurvedic herbal formulation composed of equal parts of three dried fruits: *Emblica officinalis* Amla, *Terminalia bellirica* Bibhitaki, and *Terminalia chebula* Haritaki. It has been traditionally used in Indian medicine for its rejuvenating, detoxifying, and therapeutic properties. Triphala as a combined formulation is especially notable for its antioxidant, antimicrobial and antifungal potential. It exerts free radical scavenging activity through its high polyphenol and flavonoid content, making it effective in reducing oxidative spoilage in fresh produce (Kaur & Arora, 2009). Its antimicrobial efficacy has been demonstrated against a wide range of pathogens including *E. coli*, *Salmonella spp.*, and *Candida albicans*, attributed to the synergistic action of its tannins and organic acids (Sharma et al., 2020). Given its Generally Recognized As Safe GRAS status, biodegradability, and multifunctional bioactivity, Triphala represents a sustainable and consumer-friendly alternative to synthetic additives in postharvest systems. The current study explores oxidative stability, microbial suppression, and maintenance of structural and sensory quality of tomatoes during shelf-life storage. Triphala extracts can be used to reduce the particle size in synthesizing nanoparticles. Tomatoes *Solanum lycopersicum* are nutrient-dense fruits rich in vitamins, antioxidants, and bioactive compounds. However, their climacteric nature and high moisture content make them highly perishable and remarkable wastage during the season (Perveen et al., 2015; Singh et al., 2020). Effective preservation strategies are therefore essential to maintain their quality and reduce spoilage during postharvest handling and storage (Kader, 2008). This study explores the development and application of structured edible coatings based on zein and triphala extracts for extending the shelf life of tomatoes. Through physicochemical, microbiological, and sensory evaluations, the research aims to assess the effectiveness of these coatings in minimizing postharvest losses and supporting sustainable food preservation practices.

2. Methodology

Fresh, mature, and uniform sized tomatoes *Lycopersicon esculentum* Mill. were procured from local farms in the Tirupati district, Andhra Pradesh, and carefully selected to exclude any mechanically damaged or decayed fruits. Uniform maturity and size of selected tomatoes were initially washed under running tap water and subsequently sanitized by immersion in a 4% chlorine solution for a few minutes to remove surface contaminants. They were then rinsed thoroughly with distilled water and air-dried at ambient temperature to eliminate residual moisture. For the development of edible coatings, zein protein was used at two concentrations 2.5% and 5% dissolved in 85% aqueous ethanol and stirred for 15 minutes to ensure homogeneity. Simultaneously, Triphala extract was prepared by dissolving 5% and 10% of triphala powder in 100 mL distilled water followed by heating at 75°C for 15 minutes and further stirring for 15 minutes. After resting for 6 hours at room temperature, the solution was filtered and stored for application. To formulate the structured edible coating, 50 mL of zein solution was gradually added to 100 ml of triphala extract using a liquid-liquid dispersion method while stirring continuously. Food-grade Tween-20 was added as a stabilizer to enhance the dispersion and prevent particle aggregation. The blend was filtered, rested overnight, and centrifuged at 5000 rpm for 30 minutes. The supernatant, rich in scale particles, was collected and used as the final coating formulation (Fig.1). The tomatoes were randomly divided into five treatment groups: uncoated control C, Z2.5, Z5, ZT5, and ZT10. Each tomato was dipped in its respective coating solution for one minute to ensure uniform coverage (Fig.2), then air-dried at ambient temperature 26 ± 1°C for two hours to allow proper setting of the coating film. The samples were stored in labelled plastic containers and evaluated at three-day intervals over a 22-day storage period. The study comprehensively assessed various quality attributes, including physicochemical parameters such as weight loss, moisture loss, firmness measured using a penetrometer, pH, total soluble solids TSS, titratable acidity, and lycopene content extracted using the hexane:ethanol:acetone method.. Sensory attributes such as appearance, color, taste, flavor, texture, and overall acceptability were evaluated by a panel of five trained judges using a five-point hedonic scale. Microbial stability was analyzed through total plate count, yeast and mold count using pour plate methods.

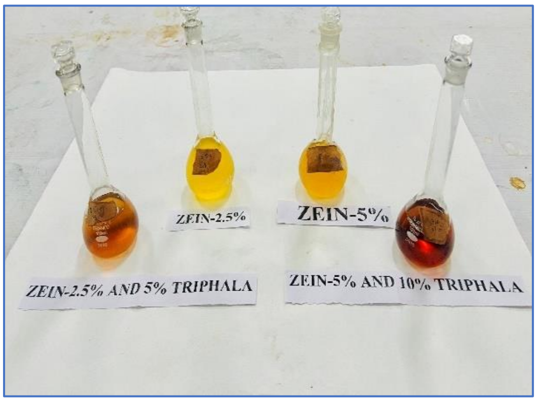

Figure 1: Zein, Zein and Triphala edible coating solutions

Figure 2: Dipping of tomatoes in edible coating solutions

3. Results

3.1 Weight loss

Physiological loss in weight PLW is a critical indicator of postharvest deterioration in fresh produce, primarily resulting from moisture loss and respiratory metabolism (AOAC, 2006). During the initial storage phase, from Day 1 to Day 9, all coated tomato samples demonstrated low levels of weight loss, while the control sample showed a more noticeable decline (Table.1), especially by Day 6. Among the coated treatments, ZT5 consistently exhibited the lowest weight loss throughout this period. By Day 9, ZT5 recorded a weight loss of only 2.19%, followed by ZT10 at 2.76%. In contrast, Z2.5 and Z5 showed higher losses of 4.51% and 3.79%, respectively, suggesting reduced effectiveness over time. The control sample, lacking any protective coating, showed rapid dehydration with an 8.25% weight loss by Day 9. By Day 12, the difference among treatments became more pronounced. ZT5 and ZT10 continued to perform well, with weight losses of 2.85% and 3.22%, respectively, while Z2.5 and Z5 increased to 4.72% and 4.75%. The control sample deteriorated quickly, reaching 8.98% loss, with visible spoilage by the following days. By Day 15, the advantage of triphala-containing coatings became clearer: ZT5 recorded a moderate weight loss of 3.37%, and ZT10 at 4.09%, while Z2.5 and Z5 rose to 5.33% and 5.60. The control sample was already spoiled at this stage. Between Day 18 and Day 22, zein-only coatings showed signs of failure, with Z2.5 reaching 6.01% loss and Z5 peaking at 6.93%, after which both spoiled by Day 22. In comparison, ZT5 and ZT10 recording only 3.71% and 5.16% losses by Day 18, and slightly increasing to 4.33% and 5.34% by Day 22 without spoilage (Fig.3).

S.No.	ZEIN %						ZEIN AND TRIPHALA %						CONTROL SAMPLE		
	2.5 %			5 %			2.5%+ 5%			5% + 10%					
	Weightg														
	Initial	Final	% Loss	Initial	Final	% Loss	Initial	Final	% Loss	Initial	Final	% Loss	Initial	Final	% Loss
Day 1	76.3	77.3	1	74.4	75.4	1	75.4	76.4	1	76.7	77.7	1	75	-	-
Day 3	74.1	72.8	1.3	75.01	73.39	1.62	76.3	75.24	1.06	75.41	74.18	1.23	75.37	72.31	3.06
Day 6	74.6	71.9	2.7	76.5	72.94	3.56	75.94	74.86	1.08	76.22	72.43	1.79	75.62	68.23	7.39
Day 9	76.72	72.21	4.51	74.74	70.95	3.79	76.51	74.32	2.19	77.63	74.87	2.76	74.35	66.1	8.25
Day 12	76.46	71.74	4.72	74.32	69.57	4.75	74.04	71.19	2.85	74.58	71.36	3.22	76.16	67.18	8.98
Day 15	75.45	72.12	5.33	76.85	71.25	5.6	75.72	72.35	3.37	75.78	71.69	4.09	75.28	spoiled	spoiled
Day 18	76.64	68.63	6.01	75.75	66.82	6.93	74.79	71.08	3.71	76.74	71.58	5.16	74.26	spoiled	spoiled
Day 22	spoiled	spoiled	spoiled	spoiled	spoiled	spoiled	76.67	72.34	4.33	75.46	70.12	5.34	spoiled	spoiled	spoiled

Table 1: Weight Loss in Tomatoes Treated with Zein, Zein-Triphala Coatings, and Uncoated Control

3.2 Moisture Content

Moisture loss is a key factor influencing fruit texture, firmness, and overall postharvest quality, as it leads to increased dehydration and shrinkage, ultimately reducing consumer acceptability. (Tchouala Tazo et al., 2023). On Day 1, all samples, including the control, started with a uniform moisture content of 3.0 ml, confirming consistency in initial hydration across all tested groups. By Day 3, a slight decline was observed, with the control sample reducing to 2.5 ml, while zein 2.5% and zein 5% maintained 2.7 ml and 2.8 ml, respectively. ZT5 and ZT10 retained the highest moisture at 2.9 ml. By Day 6, the control further dropped to 2.3 ml, indicating steady dehydration. In comparison, zein-only coatings recorded 2.6 ml Z2.5 and 2.7 ml Z5, while triphala-coated samples maintained 2.9 ml, showing their superior moisture retention. By Day 9, the control experienced a drop to 1.7 ml, confirming a faster rate of moisture loss in the absence of a protective coating. Meanwhile, zein 2.5% and zein 5% held 2.4 ml and 2.5 ml, respectively, while ZT5 retained 2.7 ml and ZT10 retained 2.8 ml. By Day 12, the control declined to 1.2 ml, reflecting severe dehydration and nearing spoilage. In contrast, Z2.5 and Z5 recorded 2.0 ml and 2.1 ml, while ZT5 and ZT10 preserved higher values of 2.4 ml and 2.5 ml, respectively. By Day 15, the control had completely deteriorated, confirming that uncoated tomatoes had reached the end of their shelf life. Z2.5 and Z5 showed reduced moisture at 1.8 ml each, while ZT5 and ZT10 retained slightly higher levels at 2.1 ml and 2.0 ml. By Day 18, Z2.5 dropped to 1.6 ml, Z5 to 1.7 ml, ZT5 to 2.0 ml, and ZT10 to 1.9 ml. By Day 22, both zein-only samples had spoiled, while ZT5 and ZT10 still retained 1.9 ml and 1.7 ml, respectively (Fig.4).

3.3 pH

The pH of tomatoes is a crucial indicator of ripening progression and microbial susceptibility during storage. A gradual increase in pH is typically associated with organic acid degradation and metabolic activity, leading to reduced acidity and accelerated spoilage (Islas-Osuna et al. 2010) (Fig.5). In the present study, a steady rise in pH was observed in all treatments over time; however, the rate of increase varied depending on the coating applied. On Day 1, all samples started with a consistent pH range, with

Z2.5 at 3.4, Z5 at 3.7, ZT5 at 3.6, ZT10 at 3.7, and the control sample at 2.9. By Day 3, a slight increase in pH was observed across all samples, with the control rising to 3.1, while Z2.5 and Z5 increased to 3.5 and 3.9, respectively. The zein and triphala-coated samples showed minimal pH fluctuation, remaining relatively stable at 3.7 ZT5 and 3.8 ZT10. By Day 6, the control sample reached 3.6, while the coated samples maintained higher pH values, with Z2.5 at 3.6, Z5 at 4.1, and both ZT5 and ZT10 holding steady at 3.7 and 3.8, respectively. By Day 9, a clear difference in pH was evident between coated and uncoated samples. The control reached 3.7, while Z2.5 rose to 3.8, Z5 to 4.3, ZT5 to 4.2, and ZT10 to 4.1. On Day 12, the control peaked at 4.1 before spoilage occurred by Day 13. Meanwhile, Z2.5 and Z5 increased to 4.0 and 4.4, respectively, and ZT5 and ZT10 maintained their levels at 4.3. By Day 15, the zein-coated samples continued rising, reaching 4.2 Z2.5 and 4.5 Z5, while ZT5 and ZT10 exhibited slightly higher pH values of 4.4 and 4.5, respectively, reflecting continued stability. By Day 18, Z2.5 and Z5 remained at 4.2 and 4.5, respectively, whereas ZT5 rose to 4.5 and ZT10 to 4.7 still within a controlled range. By Day 22, both zein-only samples Z2.5 and Z5 had spoiled, while ZT5 and ZT10 sustained pH values of 4.7 and 4.9, respectively, showing better stability at the end of the storage period.

3.4 Titratable acidity (TA)

Titratable acidity is a key quality parameter that reflects the organic acid content in tomatoes, directly influencing taste, microbial resistance, and overall postharvest physiology Valero et al., 2013. Typically, TA decreases during storage due to the utilization of organic acids as substrates in respiration and other metabolic activities. In this study, all tomato samples showed a declining trend in TA over time, but the rate of reduction varied considerably among the treatments (Fig.6). On Day 1, all tomato samples exhibited relatively high titratable acidity values, with Z2.5 at 1.14, Z5 at 1.26, ZT5 at 1.31, ZT10 at 1.46, and the control sample at 0.93. By Day 3, a slight decrease in acidity was observed across all samples. The control dropped to 0.91, while Z2.5 and Z5 recorded 1.11 and 1.22, respectively. ZT5 and ZT10 retained higher acidity levels at 1.28 and 1.39. By Day 6, the trend continued with the control decreasing to 0.89, while Z2.5 and Z5 showed values of 1.05 and 1.13, respectively. ZT5 and ZT10 again maintained better acidity retention at 1.26 and 1.36. On Day 9, the control sample declined further to 0.79, whereas Z2.5 and Z5 recorded 0.95 and 1.12. ZT5 and ZT10 sustained their acidity at 1.25 and 1.21. By Day 12, the control sample had dropped sharply to 0.53 and spoiled by Day 13. Meanwhile, Z2.5 and Z5 retained acidity at 0.95 and 1.11, while ZT5 and ZT10 remained stable at 1.22 and 1.20. By Day 15, the zein-coated samples recorded 0.96 Z2.5 and 1.11 Z5, while ZT5 and ZT10 again maintained slightly higher values of 1.18 and 1.19. On Day 18, Z2.5 showed a further decline to 0.90, Z5 at 1.06, ZT5 at 1.07, and ZT10 at 1.14. By Day 22, both zein-only samples Z2.5 and Z5 were spoiled, whereas ZT5 and ZT10 still retained acidity values of 0.96 and 1.09, respectively.

3.5 Total Soluble Solids (TSS)

Total soluble solids TSS, primarily composed of sugars and organic acids, serve as an essential indicator of fruit ripening and flavor development in tomatoes. During postharvest storage, an increase in TSS is commonly observed as starches and complex carbohydrates break down into simpler sugars, contributing to sweetness Li et al., 2016. In the current study, all tomato samples exhibited a progressive rise in TSS values over time; however, the rate and extent of this increase differed among treatments, influenced by the presence and composition of edible coatings (Fig.7). During the initial storage phase, from Day 1 to Day 9, all coated tomato samples showed moderate increases in total soluble solids TSS, while the control sample exhibited a more rapid rise, especially noticeable by Day 6. Among the coated treatments, ZT5 maintained the most consistent TSS levels, starting at 5.3 °Brix on Day 1 and rising only to 5.7 °Brix by Day 9, suggesting a slower ripening process. ZT10 followed closely, increasing from 5.1 to 5.6 °Brix during the same period. In contrast, zein-only coatings Z2.5 and Z5 showed faster increases, with Z2.5 climbing from 5.0 to 6.3 °Brix and Z5 from 4.8 to 5.5 °Brix. The control showed a steep rise from 5.0 to 5.9 °Brix by Day 6, and 6.3 °Brix by Day 9, indicating accelerated metabolic activity and sugar conversion due to lack of protective coating. By Day 12, differences in TSS among the treatments became more distinct. ZT5 and ZT10 exhibited controlled increases to 5.8 and 5.9 °Brix, respectively, while Z2.5 and Z5 reached 6.6 and 5.7 °Brix. The control sample reached 6.6 °Brix by this stage, and visible signs of over-ripening were evident. By Day 15, ZT5 and ZT10 maintained TSS levels at 6.0 and 6.1 °Brix, respectively, while Z2.5 and Z5 rose further to 6.8 and 5.8 °Brix, showing that zein-only coatings allowed a faster ripening rate. The control had already spoiled by this point. Between Day 18 and Day 22, the pattern continued Z2.5 and Z5 showed TSS values of 7.1 and 6.1 °Brix by Day 18, after which both spoiled by Day 22. In contrast, ZT5 and ZT10 continued their gradual TSS progression, reaching 6.2 and 6.6 °Brix by Day 18 and 6.4 and 6.6 °Brix by Day 22, respectively, without spoilage.

3.6 Firmness

Firmness is a critical quality parameter in tomatoes that reflects the integrity of the fruit's cellular structure and directly influences consumer acceptability, transportability, and shelf life. During postharvest storage, firmness typically declines due to enzymatic softening, cell wall degradation, and moisture loss. In this study, a consistent reduction in firmness was recorded across all treatment groups, but the rate of softening varied markedly based on the type of coating applied (Fig.8). On Day 1, all samples exhibited relatively high firmness values, with Z2.5 at 3.1, Z5 at 3.5, ZT5 at 4.4, ZT10 at 4.7, and the control sample at 3.5. By Day 3, a slight decrease in firmness was observed as part of the natural ripening process. The control sample dropped to 3.2, while Z2.5 and Z5 recorded 3.7 and 3.4, respectively. Zein and triphala coated samples, ZT5 and ZT10, retained firmness at 4.2 and 4.1. By Day 6, the control sample declined further to 3.0, while Z2.5 and Z5 showed values of 3.3 and 3.1. In comparison, ZT5 and ZT10 maintained higher firmness at 3.7 and 3.9, respectively. On Day 9, firmness in the control remained low at 3.0, whereas Z2.5 stayed at 3.5 and Z5 at 3.0. ZT5 and ZT10 continued to exhibit better texture retention with values of 3.6 and 3.7. By Day 12, the control had completely deteriorated to 2.5, indicating advanced breakdown of cellular structure. Z2.5 and Z5 dropped to 3.3 and 2.9, while ZT5 and ZT10 retained higher firmness at 3.4 and 3.6, respectively. This trend continued into Day 15, where the control had completely spoiled. Z2.5 and Z5 recorded 3.1 and 2.8, while ZT5 and ZT10 remained more stable at 3.3 and 3.5. By Day 18, Z2.5

and Z5 declined to 2.9 and 2.7, while ZT5 and ZT10 still held at 3.1 each, showing their continued structural advantage. On Day 22, both zein-only samples had spoiled, but ZT5 and ZT10 retained firmness at 3.0 and 2.9, respectively.

3.7 Lycopene Content

Lycopene is a major bioactive compound in tomatoes, responsible for their characteristic red color and valued for its potent antioxidant properties. During postharvest storage, lycopene biosynthesis typically increases as the fruit ripens, reaching peak levels before declining due to oxidative degradation or microbial spoilage (Alda et al., 2009). In the present study, a progressive increase in lycopene content was observed across all treatments until the onset of senescence. However, the rate of accumulation and subsequent stability varied depending on the type of coating applied. On Day 1, all samples showed similar lycopene content, confirming that the initial application of coatings did not alter the natural carotenoid concentration. Lycopene values were 1.168 mg/100g for Z2.5, 1.186 mg/100g for Z5, 1.165 mg/100g for ZT5, 1.152 mg/100g for ZT10, and 1.163 mg/100g for the control sample. By Day 5, lycopene levels increased due to natural ripening, with the control showing a faster rise to 1.486 mg/100g. In contrast, Z2.5 and Z5 recorded 1.366 mg/100g and 1.373 mg/100g, while ZT5 and ZT10 showed slower increases at 1.184 mg/100g and 1.178 mg/100g, respectively. By Day 10, lycopene content in the control sample rose sharply to 1.652 mg/100g, reflecting rapid ripening and metabolic changes. Meanwhile, Z2.5 reached 1.486 mg/100g and Z5 at 1.462 mg/100g, both higher than the triphala-coated samples, where ZT5 remained at 1.197 mg/100g and ZT10 at 1.185 mg/100g. By Day 15, the control had spoiled, while Z2.5 and Z5 continued to increase to 1.611 mg/100g and 1.563 mg/100g. In contrast, ZT5 and ZT10 showed slower progression at 1.204 mg/100g and 1.195 mg/100g. By Day 20, Z2.5 and Z5 had spoiled, indicating the end of their preservation potential. However, ZT5 and ZT10 continued to perform well, with lycopene levels of 1.214 mg/100g and 1.207 mg/100g, respectively.

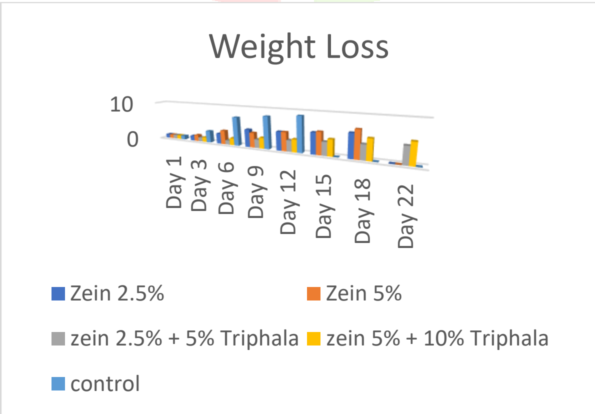

Figure 3: Weightloss of Tomatoes Treated with Zein, Zein-Triphala Coatings, and Uncoated Control

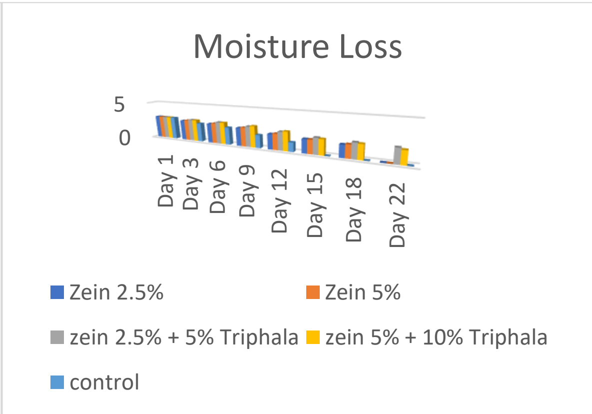

Figure 4: Moisture loss of Tomatoes Treated with Zein, Zein-Triphala Coatings, and Uncoated Control

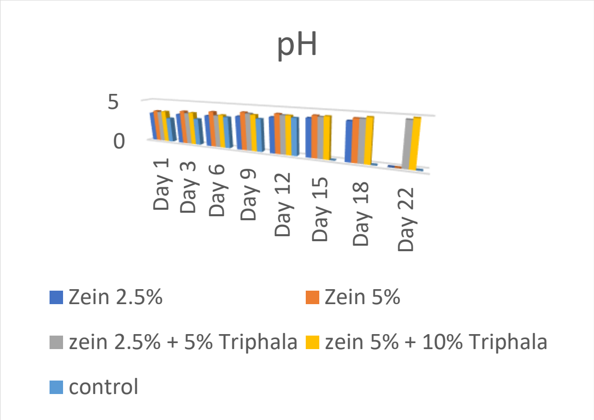

Figure 5: pH of Tomatoes Treated with Zein, Zein-Triphala Coatings, and Uncoated Control

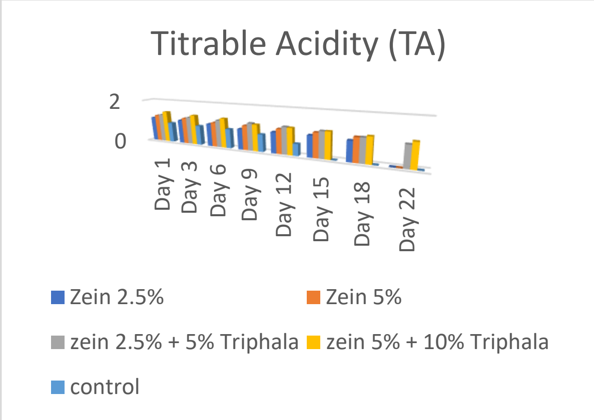

Figure 6: TA of Tomatoes Treated with Zein, Zein-Triphala Coatings, and Uncoated Control

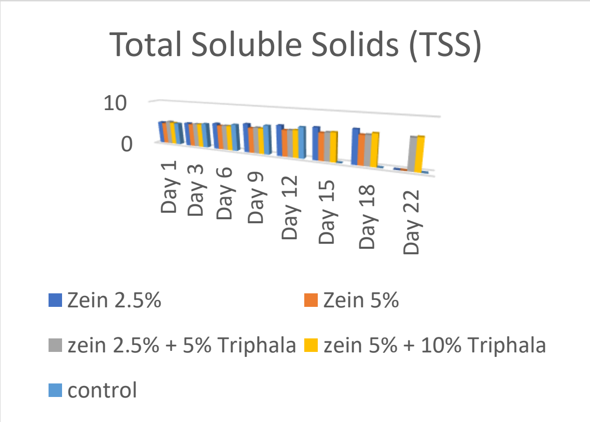

Figure 7: TSS of Tomatoes Treated with Zein, Zein-Triphala Coatings, and Uncoated Control

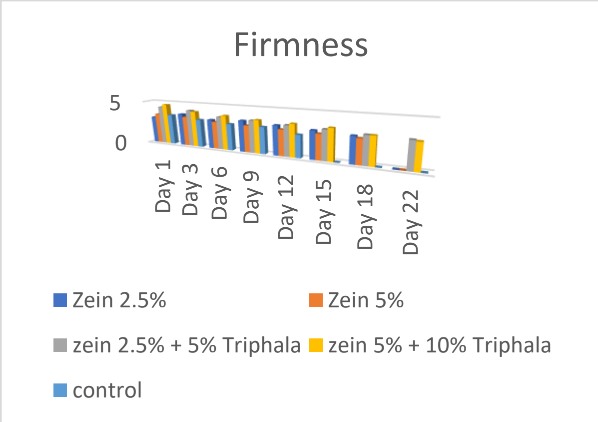

Figure 8: Firmness of Tomatoes Treated with Zein, Zein-Triphala Coatings, and Uncoated Control

3.8 Sensory Evaluation

A comprehensive sensory evaluation of tomatoes treated with zein, zein-triphala coatings, and an uncoated control was systematically conducted by a panel of five trained judges using a 5-point hedonic scale, focusing on key quality attributes appearance, color, flavor, taste, and texture throughout a 22-day storage period (Fig.9). On Day 1, all samples, including the control, exhibited uniformly high scores of 4.7 across all parameters, indicating excellent initial sensory quality. However, the uncoated control sample deteriorated rapidly, with scores for appearance, color, and flavor falling below 4.0 by Day 6 and complete spoilage occurring before Day 15. Zein-only coated samples Z2.5 and Z5 provided moderate protection, with appearance scores declining to 3.9 and 4.0 by Day 18 and spoilage occurring by Day 19. In contrast, zein-triphala formulations ZT5 and ZT10 demonstrated visual quality, maintaining appearance scores above 4.1 through Day 22. Color followed a similar trend. Although all samples began at 4.7, the control dropped to 3.9 by Day 6, reflecting rapid pigment degradation. Zein-only coatings slowed this decline slightly, reaching around 4.0 by Day 18, whereas ZT5 and ZT10 consistently maintained higher color scores above 4.2 through Day 22, indicating improved color stability. Flavor deterioration was most pronounced in the control, which dropped below the acceptable threshold 3.5 and spoiled by Day 12.

Zein-only coatings delayed flavor loss to some extent but still showed noticeable decline from Day 9 onward, reaching 4.0 or lower by Day 18. In contrast, ZT5 and ZT10 retained flavor quality more effectively, with scores of 4.3 and 4.1, respectively, by Day 22. Taste scores mirrored the trend in flavor. The control sample dropped below 4.0 by Day 6, with rapid spoilage following shortly after. Zein-only samples showed minor improvement, but by Day 18, taste scores had declined to 3.9 Z2.5 and 4.0 Z5. In contrast, ZT5 and ZT10 exhibited consistent taste retention, maintaining scores of 4.3 and 4.1, respectively, at the end of the storage period. Among all sensory attributes, texture revealed the clearest distinction between treatments. The control sample experienced rapid softening, with texture scores falling to 3.4 by Day 12 and spoilage occurring soon after. Zein-only coatings extended firmness retention up to Day 15 but dropped below 4.0 by Day 18 and spoiled by Day 19. Meanwhile, ZT5 and ZT10 showed texture scores of 4.2 and 4.0 on Day 22, respectively. Texture evaluation revealed the most pronounced differentiation among the treatments, serving as a key indicator of structural integrity and freshness. The uncoated control sample exhibited rapid softening, with texture scores falling sharply to 3.4 by Day 12, followed by complete spoilage shortly thereafter. Zein-only treatments Z2.5 and Z5 provided moderate improvement, maintaining acceptable firmness until Day 15; however, by Day 18, their texture scores declined below 4.0, and both samples reached spoilage by Day 19. By Day 22, ZT5 and ZT10 retained texture scores of 4.2 and 4.0, respectively.

Figure 9: Tomato samples coated with zein, zein with triphala and control on day 1,10,18,22.

3.9 Microbial analysis

Total Plate Count (TPC)

Total plate count TPC serves as a key microbiological indicator to assess the overall microbial load and sanitary quality of fresh produce during storage (Chien et al., 2007; Jarvis, 2016). On Day 1, microbial counts were relatively low across all samples, with Z2.5 recording 3.83 log CFU/g, Z5 at 3.73 log CFU/g, ZT5 at 3.67 log CFU/g, and ZT10 at 3.84 log CFU/g. The control sample started at 2.57 log CFU/g, but due to the absence of any protective coating, its microbial load increased rapidly over time. By Day 3, a mild increase in microbial activity was observed. The control rose to 3.73 log CFU/g, while Z2.5 and Z5 showed 3.53 and 3.59 log CFU/g, respectively. ZT5 and ZT10 remained relatively more stable, recording 3.43 and 3.76 log CFU/g, respectively. By Day 6, the control sample exhibited a rapid microbial surge, reaching 5.63 log CFU/g, while zein-only coatings showed slower microbial growth with Z2.5 at 2.85 log CFU/g and Z5 at 3.36 log CFU/g. ZT5 and ZT10 were more effective in microbial control, recording 3.28 and 3.71 log CFU/g, respectively. On Day 9, the control accelerated to 7.78 log CFU/g, confirming rapid spoilage. In contrast, Z2.5 and Z5 dropped to 2.74 and 2.12 log CFU/g, respectively, while ZT5 and ZT10 maintained better stability at 2.95 and 3.66 log CFU/g. By Day 12, the control exceeded the microbial acceptability threshold at 9.19 log CFU/g and was spoiled. Zein-coated samples showed continued microbial suppression, with Z2.5 at 2.48 and Z5 at 1.93 log CFU/g. ZT5 and ZT10 held steady at 2.78 and 3.27 log CFU/g. By Day 15, the control sample remained spoiled, while zein-only coatings still retained acceptable microbial counts at 1.86 Z2.5 and 1.78 Z5 log CFU/g. ZT5 and ZT10 showed microbial loads of 2.61 and 2.73 log CFU/g, respectively, confirming prolonged antimicrobial action. By Day 18, microbial levels in Z2.5 and Z5 dropped further to 1.57 and 1.25 log CFU/g, while ZT5 and ZT10 remained moderately controlled at 2.47 and 2.37 log CFU/g. By Day 22, Z2.5 and Z5 reached spoilage, whereas ZT5 and ZT10 still exhibited microbial loads of 2.34 and 2.14 log CFU/g, respectively (Fig.10,12).

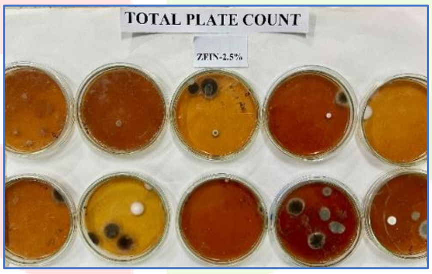

Figure 10: The total plate count of zein and triphala samples

3.10 Yeast and Mold Count (TYMC)

Yeasts and molds are major contributors to the postharvest spoilage of tomatoes, particularly under ambient conditions where high moisture and softening of tissue create an ideal environment for fungal proliferation (Chien et al., 2007; Jarvis, 2016). On Day 1, all samples exhibited relatively low yeast and mold counts, with Z2.5 recording 3.34 log CFU/g, Z5 at 3.68 log CFU/g, ZT5 at 3.44 log CFU/g, and ZT10 at 3.27 log CFU/g. The control sample started at 3.15 log CFU/g, indicating comparable initial microbial loads across all treatments. By Day 3, yeast and mold proliferation became apparent in the control sample, which rose sharply to 4.23 log CFU/g. In contrast, coated samples demonstrated better control, with Z2.5 at 3.27, Z5 at 3.45, ZT5 at 3.28, and ZT10 at 3.03 log CFU/g. By Day 6, the control exhibited a substantial increase in fungal load, reaching 6.76 log CFU/g, confirming the absence of any microbial barrier. Meanwhile, Z2.5 and Z5 showed reduced counts of 2.85 and 3.26 log CFU/g, respectively. ZT5 and ZT10 performed better, maintaining lower levels at 2.91 and 2.87 log CFU/g, respectively. By Day 9, the control surged to 7.44 log CFU/g, showing rapid deterioration. Coated samples retained lower values, with Z2.5 at 2.72, Z5 at 2.94, ZT5 at 2.78, and ZT10 at 2.72 log CFU/g, continuing to demonstrate microbial stability. By Day 12, the control reached 9.47 log CFU/g, far beyond acceptable thresholds for fresh produce, confirming spoilage. Zein-coated samples still retained control, with Z2.5 at 2.64 and Z5 at 2.85 log CFU/g. ZT5 and ZT10 showed even better stability at 2.36 and 2.51 log CFU/g, respectively, demonstrating prolonged antifungal action. By Day 15, the control sample was fully spoiled, while Z2.5 and Z5 recorded 2.58 and 2.76 log CFU/g. ZT5 and ZT10 remained effective with values of 2.17 and 2.38 log CFU/g, respectively. By Day 18, the control remained spoiled, while microbial counts in Z2.5 and Z5 further dropped to 2.42 and 2.52 log CFU/g. ZT5 and ZT10 sustained lower fungal levels at 2.06 and 2.23 log CFU/g, confirming the extended antifungal activity. On Day 22, Z2.5 and Z5 had reached spoilage, while ZT5 and ZT10 maintained microbial loads of 1.84 and 1.28 log CFU/g, respectively (Fig.11,12).

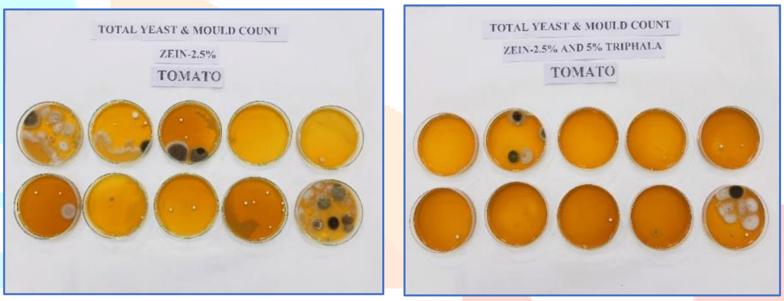

Figure 11: The total yeast and mould count of zein and triphala samples

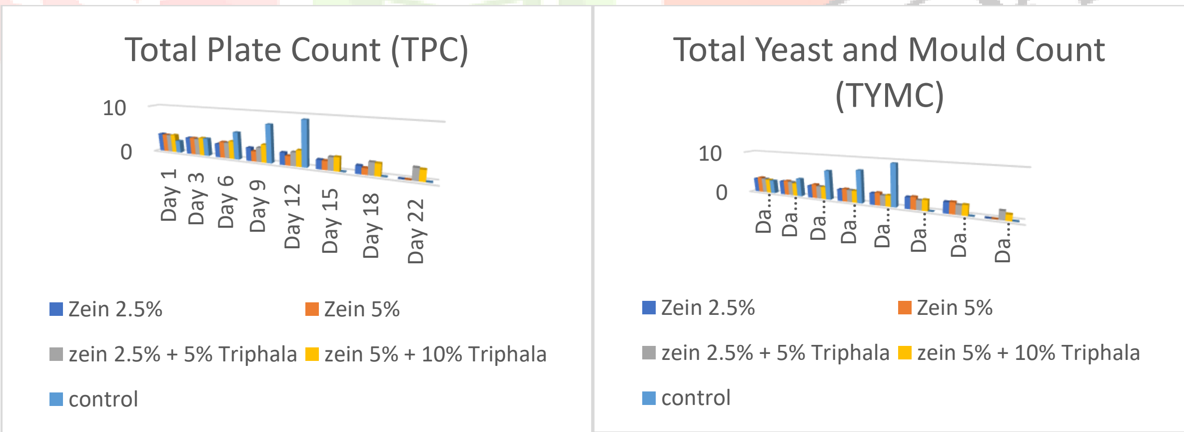

Figure 12: TPC & TYMC of Tomatoes Treated with Zein, Zein-Triphala Coatings, and Uncoated Control

4. Discussion

The current study highlights the potential of zein and triphala-based edible coatings as an effective postharvest strategy to extend the shelf life and preserve the physicochemical, microbial, nutritional, and sensory quality of fresh tomatoes stored under ambient conditions. The outcomes demonstrate that the ZT5 formulation consistently outperformed other treatments, including zein-only coatings, across multiple quality indices, validating the synergistic benefits of combining natural protein and polyphenol-rich botanical extracts in a structured matrix. The comprehensive evaluation of all physicochemical and microbial parameters clearly demonstrates the superior performance of zein and triphala-based edible coatings in extending the postharvest shelf life and maintaining the overall quality of tomatoes during storage. Weight loss, a critical indicator of dehydration and freshness, increased progressively in all samples; however, tomatoes coated with zein-triphala formulations ZT5 and ZT10 consistently exhibited lower weight loss compared to zein-only and control samples. Z2.5 and Z5 recorded sharp increases after Day 9 and reached spoilage by Day 22, while ZT5 and ZT10 maintained structural integrity and delayed spoilage, showing that triphala enhanced the coating's water barrier properties and slowed moisture loss. Moisture content further supported this trend. Triphala-based coatings retained higher moisture levels throughout storage, confirming their role in reducing transpiration. ZT5 and ZT10 retained moisture even by Day 22, while zein-only samples dried out earlier and spoiled by Day 19. This confirmed that triphala addition improved film integrity, helping reduce water vapor permeability and thus extending shelf life. In terms of pH stability, triphala-based coatings again proved superior. The control sample and zein-only coatings showed faster pH increases, a sign of ripening and microbial activity. In contrast, ZT5 and ZT10 exhibited slower pH increases throughout storage, indicating delayed ripening and microbial suppression. This was attributed to the bioactive compounds in triphala, known for their antimicrobial and antioxidant effects. Total soluble solids TSS increased in all samples, reflecting ripening-associated sugar accumulation. However, zein-triphala samples showed a more gradual rise in TSS, suggesting slower metabolic conversion of carbohydrates. ZT10 maintained the most controlled increase, confirming delayed senescence and metabolic regulation due to the coating's protective action. A similar trend was seen in firmness retention, where ZT5 and ZT10 outperformed zein-only and control groups. Zein-triphala samples maintained better texture and resistance to softening throughout the storage period. This was likely due to the combined effect of moisture retention, reduced enzymatic activity, and delayed cell wall breakdown under the protective coating. Lycopene content, an indicator of ripening and oxidative stress, increased faster in control and zein-only samples. Meanwhile, ZT5 and ZT10 demonstrated slower lycopene accumulation, suggesting that triphala helped regulate carotenoid biosynthesis, likely by reducing oxidative degradation. This extended the visual and nutritional quality of the tomatoes. Microbiologically, both Total Plate Count TPC and Total Yeast and Mould Count TYMC provided strong evidence of the antimicrobial efficacy of the coatings. The control sample quickly exceeded acceptable microbial thresholds, while zein-only coatings delayed spoilage moderately. However, ZT5 and ZT10 demonstrated lower microbial loads throughout storage, even at later stages, indicating long-lasting antimicrobial protection. Triphala's polyphenolic content likely contributed to this, inhibiting microbial colonization and proliferation over time.

Overall, the study clearly confirms that the integration of triphala extract into zein coatings improved postharvest preservation. Across all measured parameters weight loss, moisture content, pH, TSS, firmness, lycopene, TPC, and TYMC the zein-triphala formulations outperformed zein-only and control samples. Among the tested formulations, ZT10 consistently provided the most extended shelf life and maintained the best quality, followed closely by ZT5. These findings support the use of zein-triphala nano coatings as a promising, natural solution for enhancing the storage stability and quality of tomatoes.

5. Conclusion

This study confirms the effectiveness of zein and triphala-based edible coatings as a natural and sustainable postharvest strategy for extending the shelf life and preserving the quality of fresh tomatoes under ambient conditions. Among all treatments, the ZT5 formulation consistently showed the most favourable performance, followed closely by ZT10. The inclusion of triphala enhanced the coating's barrier properties, resulting in reduced weight and moisture loss, improved firmness retention, and delayed spoilage. Acidity-related parameters such as pH, titratable acidity TA, and total soluble solids TSS followed similar trends, with zein-triphala coatings effectively moderating their progression by slowing ripening and maintaining metabolic stability. Additionally, the coatings provided strong antimicrobial protection, as indicated by lower total plate count TPC and yeast and mould count TYMC. Sensory evaluations further supported these findings, with ZT5 and ZT10 maintaining superior scores in appearance, color, flavor, taste, and texture up to Day 22. Overall, zein-triphala coatings, particularly ZT5, offer a promising, consumer-friendly approach for improving the postharvest preservation of tomatoes and similar perishable produce.

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Compliance with ethical Standards

Conflict of interests: The authors declare no conflict of interest.

Ethical approval: This article does not contain any studies with human participants or animals performed by any of the authors.

Informed consent: Informed consent was obtained from all individual participants included in the study.

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