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Application of Encapsulated Garlic Extract Coatings on Tomatoes

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ABSTRACT: Edible coatings containing natural bioactive compounds have gained considerable attention as a sustainable approach for extending the postharvest shelf life of fresh produce. The present work aimed at developing a starch–gelatin edible coating containing microencapsulated garlic extract encapsulated in bitter gourd seed protein nanoparticles and evaluated its effectiveness in maintaining the quality of tomatoes stored at ambient temperature (25°C) for 20 days. Tomatoes were coated with different concentrations of encapsulated garlic extract (0, 0.5, 1.0 and 2.0%) and subjected to storage to assess their physicochemical quality attributes. Coated tomatoes exhibited lower moisture loss than the uncoated control, demonstrating that the coatings helped retain moisture and delay quality deterioration during storage. The coatings also helped to maintain relatively stable TSS levels and slow changes in pH and titratable acidity during storage. In addition, coated fruits showed better color retention as reflected by lower browning index values and improved appearance. While all treatments showed reduction in ascorbic acid and an increase in lycopene content as part of the natural ripening process, the coated tomatoes generally showed better retention of the nutritional quality throughout storage. Among all the treatments,, the 2% encapsulated garlic extract coating showed the best performance in reducing weight loss and maintaining the physicochemical quality attributes of tomatoes during the storage period. Overall, the incorporation of encapsulated garlic extract into edible coating matrix enhanced its ability to delay ripening-related changes and maintain tomato quality during storage. These results indicate that bitter gourd seed protein nanoparticle-encapsulated garlic extract has strong potential as a functional ingredient in active edible coatings for postharvest preservation of tomatoes.

1. INTRODUCTION

The postharvest deterioration of fresh fruits and vegetables remains a key problem in preserving food security and the sustainability of food systems around the world. Horticultural commodities experience many quantitative and qualitative losses along the postharvest supply chain due to high moisture content, continued metabolism, and sensitivity to microbial spoilage. The Food agriculture organization (FAO) estimates that about 13.3% of food lost between harvest and retail, with the highest commodity-specific losses occurring in fruits and vegetables at 25.4% in 2023, because of their highly perishable nature and vulnerability to handling and storage related losses (Taglioni, Moncayo, & Fabi, 2023). These losses are primarily attributed to physiological senescence, moisture loss, oxidative degradation, microbial spoilage and inadequate postharvest handling practices. Beyond the economic losses, postharvest waste also leads to the loss of precious resources, such as water, energy, and agricultural inputs, which further strain environmental pressures and undermines food system sustainability. Therefore, developing sustainable strategies for maintaining quality and shelf life of fresh produce has been a major focus in food science and post harvest research (Q. Ali et al., 2024).

Tomato is one of the most cultivated and consumed horticultural crops in the world due to its nutritional and sensory properties and the high concentration of bioactive compounds including lycopene, b-carotene, vitamin C and phenolic compounds. Tomato fruit is an important vegetable crop, both economically and nutritiously, but it is extremely susceptible to postharvest deterioration, because of its high water content, high respiratory activity, and climacteric ripening characteristics (Kaur, Somasundram, Razali, & Ahmed, 2024). After harvest, tomatoes experience a series of physiological and biochemical processes that accelerate fruit softening, senescence and loss of overall quality, such as increased ethylene production, cell wall degradation, pigment changes, water loss, and membrane damage. Further, the fruit surface is a good substrate for the growth of spoilage microorganisms leading to high levels of fruit loss during storage, transport and marketing. However, effective preservation strategies which can prolong the shelf life and retain the marketability of fresh tomato by delaying ripening, inhibiting microbial growth, and maintaining physicochemical quality is critical (de Medeiros, de Oliveira, Queiroga, & de Souza, 2024).

Proteins have attracted significant attention as edible coating materials because of their superior film-forming ability, biodegradability, and their capacity to include a variety of bioactive additives. Protein based coatings create cohesive film networks with favorable mechanical characteristics and barrier properties, and also allow for incorporation and controlled delivery of functional bioactive compounds. Recent developments in nanotechnology have expanded the potential applications of protein-based materials by enabling the fabrication of protein nanoparticles with improved surface characteristics, interfacial properties and functional performance. Nano-engineered protein systems have shown enhanced encapsulation efficiency and controlled release capabilities, highlighting their potential as functional components in active edible coatings designed to improve food preservation (Nabgui, 2022).

In recent years, advanced food applications of underutilized plant proteins have been gaining considerable interest, both for sustainability and for value-added utilization of agro-industrial by-products. The bitter gourd (*Momordica charantia* L.) seeds are a good source of proteins with interesting functional properties and are discarded during processing. The seeds of bitter gourd have been previously shown to possess good emulsifying, water-binding, and film-forming properties that make them potential matrix materials for biodegradable formulations (Yan et al., 2021). In addition, the reduction of particle dimensions to the nanoscale can also improve the functionality of proteins by increasing their surface reactivity and molecular interactions, thus increasing their potential use in active food packaging and delivery systems (Qiu et al., 2020).

The incorporation of plant-derived bioactive compounds has attracted considerable attention as functional ingredients in edible coatings due to their potent antioxidant and antimicrobial activities. Garlic (*Allium sativum* L.) has gained significant attention because it contains organosulfur compounds including allicin which exhibits strong antimicrobial activity against numerous foodborne and food spoilage microorganisms. In addition garlic extract also exhibited antioxidant activity that can help oxidative deterioration and contribute to the preservation of fresh produce quality throughout storage. Despite their promising bioactivities, the utilization of garlic bioactives remains challenging due to their volatile nature, susceptibility to degradation and environmental instability, emphasizing the importance of suitable encapsulation and delivery systems (Shang et al., 2019).

Encapsulation protects sensitive bioactive compounds from environmental conditions, thereby improving their stability and functional efficacy within food systems. Protein-based nanocarriers are considered promising interest due to their excellent biocompatible and degradability and ability to interact with various bioactive molecules. Incorporating garlic extract into nano-protein matrix enhances the retention of volatile compounds, enables controlled release and protect them from early degradation. Such nano-enabled delivery systems boost the efficacy of encapsulated bioactive compounds while providing chances for the development of active coatings that effectively extent the shelf life and maintain food preservation performance (Zhou, Zhang, Han, Liu, & Asemi, 2025).

Therefore, the present study aimed to develop an edible coating formulated from nano-reduced bitter gourd seed protein, incorporated with garlic extract, followed by an assessment of its efficacy in maintaining the quality attributes and extending the shelf life of tomatoes during storage. The physicochemical characteristics of the encapsulated system were evaluated the effectiveness of the developed coating to preserve tomato quality and enhance shelf life during storage.

2. MATERIAL AND METHOD

Fresh tomatoes at the mature red stage and free from visible defects, were procured from the agricultural farm of Eternal University, Baru Sahib, Himachal Pradesh, India, and used for coating and storage studies. Bitter gourd seed protein (BGS) isolate (purity 91.23%) was obtained from the research centre for food technology of Eternal University, Baru Sahib, and

Himachal Pradesh, India. Analytical-grade chemicals and reagents employed in this study were purchased from Hi-media Laboratories Pvt. Ltd., Mumbai, India.

2.1 Preparation of nano-reduced bitter gourd seed protein encapsulating garlic extract

Bitter gourd seed protein nanoparticles were prepared using a pH- shifting method followed by high-pressure homogenization to the procedure described by (Teng, Luo, & Wang, 2012). Garlic extract was encapsulated in the protein nanoparticles via protein-polysaccharide complex coacervation, employing gum arabic as a wall material to the method reported by (Devi, Sarmah, Khatun, & Maji, 2017). The resulting encapsulated powder was freeze-dried and stored at -20 degree for further use in coating formulations.

2.2 Preparation and application of edible coatings

The coating solution was prepared by dissolving starch (5g) and gelatin (1 g) in 100 ml of distilled water. The mixture was heated at 80°C for 10 min under magnetic stirring. Glycerol (8 mL) was added as a plasticizer, and stirring was continued for 20 min. The solution was then cooled to room temperature. Then encapsulated garlic extract was added at concentrations of 0.5%, 0.1% and 2% (w/v) by slowly sprinkling the powder into the coating solution under continuous stirring. The mixture was further homogenized at 800 rpm for 3 min to obtain a uniform coating solution and kept for 15 min to remove air bubbles.

Fresh tomatoes were washed with distilled water, sanitized with 70% ethanol for 2 min and air-dried at room temperature. The fruits were divided into five groups; control (C), coating without encapsulated garlic extract (T1), coating containing 0.5% encapsulated garlic extract (T2), coating containing 1% encapsulated garlic extract (T3) and coating containing 2% encapsulated garlic extract (T4). Tomatoes were dipped in the respective coating solutions for 1 min and then air-dried at room temperature until a thin film was formed on the tomato surface. The coated and uncoated tomatoes were stored at 25°C for further analysis. The samples were evaluated for various parameters on 0, 5, 10, 15 and 20 days of storage.

The quality of coated and uncoated tomatoes during storage was assessed through various physicochemical analyses.

2.3 Determination of weight loss

The weight loss of tomatoes during storage was determined following the method described by (de Oliveira Filho et al., 2022) from the Association of Official Analytical Chemists (AOAC). Tomato was weight from the initial day of storage and at predetermined intervals every 5 days over 20 days. The percentage of weight loss was calculated from the difference between the initial and final weights using the following equation:

$$\text{Weight loss (\%)} = \frac{(\text{Initial weight} - \text{Final weight})}{\text{Initail weight}} \times 100 \qquad \text{Eq. 1}$$

2.4 Total soluble solids (TSS), pH, and titratable acidity

The TSS (°Brix) and pH of tomato samples were determined according to the method described by (de Oliveira Filho et al., 2022).Tomato slurry was prepared and used for TSS content using an Atago pal-α digital refractometer and for pH using a digital pH meter Eutech pH 2700 Instrument. Titratable acidity was determined following AOAC method 942.15, (AOAC, 2000). where 5 g of tomato slurry was dissolved in 100 ml of distilled water and titrated against 0.1 N NaOH using 1 % phenolphthalein as an indicator. The results were expressed as percentage citric acid and calculated using the following equation:

$$\text{Titratable acidity (\%)} = \frac{\text{V NaOH x 0.1 x}\frac{100}{25}}{\text{sample weight (g)}} \times 100\% \qquad \text{Eq. 2}$$

Where, V is the volume of NaOH used in mL,

N is the normality of NaOH

W is the sample weight.

2.5 Color measurement

The surface colour of tomatoes was measured a Hunter colorimeter (Model D25, Hunter Associates Laboratory Inc., Reston, VA, USA).Colour values were recorded in terms of L* (lightness), a*(redness) and b*(yellowness). The total color difference ((ΔE) was calculated using colour values of fresh tomatoes on day 0 as the reference according to the following equation:

$$\Delta E = \sqrt{(L^* - L_o).^2 + (a^* - a_o).^2 + (b^* - b_o).^2} \quad \text{Eq. 3}$$

Where,

L_o, a_o and b_o are colorimetric parameters of tomatoes sample at day 0.

2.6 Ascorbic acid

The ascorbic acid content was determined by iodometric titration (Wibowo et al., 2023). 5 g of tomato pulp was dissolved in 50 ml of distilled water and filtered. An aliquot 25 of the filtrate was titrated with 0.01 N iodine solution using 1 % starch solution as an indicator. The results were expressed as mg/100 g fresh weight and calculated using Eq. (4):

$$\text{Vit C} = \frac{\text{V Iodium x } 0.01 \text{ x } \frac{100}{25} \text{ x } 88}{\text{sample weight (g)}} \times 100 \quad \text{Eq. 4}$$

2.7 Lycopene content

Lycopene content was determined following the method of (Fish, Perkins-Veazie, & Collins, 2002) with slight modifications. Take fresh 5g tomato sample was transferred into an iodine flask and mixed with 25 mL of a solvent mixture containing acetone, ethyl acetate and n-hexane (2:1:1). The mixture was shaken for 15 min, followed by the addition of 10 mL distilled water. After gentle shaking, the mixture was allowed to stand for 10 facilitate phase separation. the upper hexane layer containing lycopene was collected and the absorbance was measured at 503 nm using a UV-visible spectrophotometer. Lycopene content was calculated using Eq. (5) and expressed as mg/kg fresh weight.

$$\text{Lycopene (mg/kg)} = \frac{\text{A } 503 \times 537 \times \text{V}}{172 \times \text{W}} \quad \text{Eq. 5}$$

Where,

A503= is the absorbance at 503 nm.

172= coefficient of lycopene in n-hexane

537= molecular weight of lycopene

V= total volume of extract (mL)

W= weight of sample (g).

2.8 Statistical analysis

The SPSS software (version 16.0, SPSS Inc., Chicago, USA) was used to conduct statistical analyses. All the experiments were carried out in triplicate, and the results are reported as mean and standard deviation. One-way analysis of variance (ANOVA) followed by Duncan's multiple-range test was used for comparison of means, and the statistical significance was taken as $p < 0.05$.

3. RESULTS AND DISCUSSION

The results are presented systematically, beginning with the evaluation of the physicochemical quality attributes of coated and uncoated tomatoes during storage. Changes in weight loss, total soluble solids, pH, titratable acidity, colour parameters, ascorbic acid and lycopene content were assessed to determine the effectiveness of the developed coating formulations. Furthermore, the effect of encapsulated garlic extract on the preservation of tomato quality and the extension of shelf life was evaluated and discussed.

3.1 Determination of weight loss

The effect of edible coating formulations on tomato weight retention during storage is shown in Table 1. A gradual decrease in fruit weight was observed across all treatments throughout the 20-day storage period, indicating continuous moisture loss associated with transpiration and respiration processes. However, the extent of weight loss was significantly varied among the different treatments. The uncoated control exhibited the highest weight loss **(11.97%)**, with weight retention decreasing from **87.38%** to **75.41%** over the storage period. In contrast, coated tomatoes showed improved better weight retention, indicating the effectiveness of the edible coatings in reducing moisture loss during storage. Among the coated samples, T4 showed the lowest weight loss **(8.56%)**, followed by T2 **(8.84%)**, T3 **(9.10%)**, and T1 **(11.52%)**.

The higher weight loss recorded in the control treatment may be attributed to the absence of a protective barrier, allowing unrestricted transpiration and respiration metabolism, which increased moisture loss during storage. In contrast, the starch gelation coatings effectively reduced weight loss by forming semi-permeable membranes around the fruit surfaces, thereby limiting water vapor diffusion and slowing respiration. This protective layer helped maintain fruit moisture content and delayed dehydration throughout the storage period. Similar findings were reported by (S. Ali, Hassan, Ejaz, Arshad, & Sabir, 2024), who observed that biopolymer coatings effectively reduced moisture loss in tomatoes by forming a protective layer that restricted transpiration and gas exchange during storage. The reduced weight loss recorded in fruits coated with garlic extract incorporated formulations, particularly the treatments containing encapsulated garlic extract may be associated with the increased barrier ability of the coating matrix, which restricted moisture transmission and helped maintain fruit weight throughout storage. Similar reductions in weight loss have also been observed for active edible coatings enriched with plant-derived extracts, which led to better barrier properties and improved postharvest quality (Younis et al., 2025). Significantly, the treatments T4 exhibited the highest weight retention (86.77%), indicating that the higher garlic extract concentrations improved coating efficiencies and maintaining fruit quality during storage.

Table1: Weight retention (%) of tomatoes during storage at 25°C.

Treatments	Day 0	Day 5	Day 10	Day 15	Day 20
Control	85.66 ± 0.25^{eA}	82.38 ± 0.25^{eB}	80.06 ± 0.21^{ec}	77.95 ± 0.20^{eD}	75.41 ± 0.31^{eE}
T1	92.25 ± 0.26^{dA}	89.44 ± 0.20^{dB}	86.99 ± 0.30^{dc}	84.77 ± 0.21^{dD}	81.62 ± 0.35^{dE}
T2	92.67 ± 0.21^{cA}	89.58 ± 0.21^{cB}	87.39 ± 0.31^{cc}	85.55 ± 0.25^{cD}	84.48 ± 0.25^{cE}
T3	93.01 ± 0.20^{bA}	90.11 ± 0.20^{bB}	87.67 ± 0.25^{bc}	85.71 ± 0.30^{bD}	84.55 ± 0.20^{bE}
T4	94.89 ± 0.30^{aA}	92.07 ± 0.25^{aB}	89.85 ± 0.25^{ac}	87.90 ± 0.31^{aD}	86.77 ± 0.21^{aE}

Values are expressed as mean ± SD. Lowercase superscripts indicate descriptive ranking among treatments within each day (vertical comparison), while uppercase superscripts indicate descriptive ranking across storage days within each treatment (horizontal comparison).

3.2 Total soluble solids (TSS), pH, and titratable acidity

The effect of coating treatments on the TSS content of tomatoes during storage is presented in **Table 2** below. The TSS values showed slightly changes during storage period, ranging from 3.27 to 5.06 °Brix. Among the treatments, T4 recorded the highest TSS value (4.10 °Brix) at the end of storage, while T3 exhibited the lowest (3.43 °Brix).The relatively stable TSS values suggest that the coatings moderated metabolic activity and delayed ripening related changes. The slight variations observed may be attributed to the simultaneous formation of soluble sugars from carbohydrates and the utilization of these sugars during respiration. Comparable results were observed by (Qubbaj & Daraghmah, 2025) who reported that edible

coatings effectively preserved soluble solids content of tomatoes throughout storage. Changes in pH during storage are shown in Table 3. A gradual increase in pH was observed in all treatments, indicating progressive ripening and depletion of organic acids. The Control exhibited the highest value (4.68) after 20 days of storage, whereas tomatoes coated with encapsulated garlic extract (T2-T4) showed comparatively lower values. Among the treatments T3 maintained the lowest pH value (4.44) at the end of storage, suggesting better preservation of fruit acidity. The slower increase in pH values observed in coated tomatoes may be attributed to reduced respiration and delayed metabolic changes. Similar trends have also been reported in coated tomatoes and other fresh fruits and vegetables, where edible coatings helped preserve organic acids and delaying ripening-induced changes (Qubbaj & Daraghmah, 2025). The effect of coating treatments on titratable acidity (TA) is presented in Table 4. TA gradually decline in all samples throughout the storage period, indicating the utilization of organic acids during respiration and ripening. The control exhibited the highest acidity at day 0 (2.43%) and dropped to 0.42% by 20 days. Although coated tomatoes also showed a decline in acidity was lower in treatments containing encapsulated garlic extract, particularly T3 and T4 when there was garlic extract coating. The reduction in TA during storage may be attributed to the utilization of organic acids as respiratory substrates and their conversion into sugars and other metabolites during the ripening process. The slower decline observed in coated tomatoes indicates that the coatings reduced respiration and delayed ripening biochemical changes. Comparable declines in titratable acidity have been reported in coated tomatoes and other types of fresh produce, where edible coatings helped retain organic acids and maintain quality during storage (Lakshan, Senanayake, Liyanage, & Lankanayaka, 2024). Overall, the results of the present study suggest that the encapsulated garlic extract coating were effective in maintaining the physicochemical quality of tomatoes by stabilizing soluble solids, slowing Ph increase and reducing the loss of organic acids during storage.

Table2: physicochemical properties (TSS, pH and TA)

Treatment	TSS (0 d)	TSS (20 d)	pH (0 d)	pH (20 d)	TA (0 d)	TA (20 d)
Control	4.50 ± 0.15^{cA}	4.04 ± 0.14^{bB}	4.29 ± 0.10^{bB}	4.68 ± 0.24^{aA}	2.43 ± 0.64^{aA}	0.42 ± 0.19^{aB}
T1	4.76 ± 0.16^{bA}	3.84 ± 0.15^{cB}	4.26 ± 0.14^{cB}	4.66 ± 0.10^{aA}	2.38 ± 0.26^{bA}	0.34 ± 0.19^{bB}
T2	5.06 ± 0.19^{aA}	4.01 ± 0.16^{bB}	4.27 ± 0.10^{cB}	4.56 ± 0.27^{bA}	2.34 ± 0.26^{cA}	0.34 ± 0.19^{bB}
T3	4.48 ± 0.16^{cA}	3.43 ± 0.14^{dB}	4.24 ± 0.16^{cB}	4.44 ± 0.08^{cA}	2.13 ± 0.26^{dA}	0.25 ± 0.12^{cB}
T4	4.59 ± 0.17^{cA}	4.10 ± 0.15^{aB}	4.36 ± 0.15^{aB}	4.60 ± 0.19^{bA}	2.09 ± 0.19^{dA}	0.21 ± 0.07^{cB}

Values are expressed as mean ± SD. Lowercase superscripts indicate descriptive ranking among treatments within each day (vertical comparison), while uppercase superscripts indicate descriptive ranking across storage days within each treatment (horizontal comparison).

3.3 Color

The effects of different coating treatments on the color characteristics of tomatoes during storage, including L*, a*, b*, chroma (C*), hue angle (h°), browning index (BI) and total colour value (E*) are presented in **Tables X and Y**. Changes in the colour attributes are important indicators of ripening and quality changes in tomatoes during storage. Overall, coated tomatoes maintained their colour retention and greater stability throughout the storage period compared to uncoated control tomato. A slight decrease in L* was observed during storage, indicating a gradual loss fruit lightness. The control exhibited a progressive increase in a* values reflecting the development of red pigmentation linked with normal ripening. Conversely, tomatoes coated with encapsulated garlic extract showed minor variations in color parameters, suggesting the ability of the coating slowed the ripening and preserve the visual quality for a longer duration. This effect could be explained by the semi-permeable barrier likely contributed to restrict oxygen availability and reduced respiration rates, which in turn slowing pigment changes linked with ripening, including chlorophyll breakdown and the accumulation of carotenoids. Similar observations have been reported for coated tomatoes, where the coatings decreased respiration and ethylene driven metabolic activities, thereby slowing pigment changes associated during ripening (Lakshan et al., 2024). Previous studies on tomatoes

coated with gum arabic, starch based coating, essential oil enriched edible films, where delayed pigment changes resulting in better color preservation of fruit during storage (A. Ali, Maqbool, Ramachandran, & Alderson, 2010; Wibowo et al., 2023).

The relatively stable C* and h° values that were observed in coated fruits further indicate better color stability and overall appearance during storage. Furthermore, fruits treated with encapsulated garlic extract exhibited lower browning index (BI) values than the control, suggesting delayed senescence and a decrease in the degradation of the pigments. The lower BI values observed in coated tomatoes suggest reduced oxidative deterioration, during storage. This may be attributed to the protective barrier provided by the edible coatings, which limited the oxygen exposure and minimize the enzymatic browning reactions. Comparable findings been reported for tomatoes and other fresh products coated with bioactive edible films, which helped decrease browning and improved visual quality(Ameer et al., 2024; Vieira et al., 2016).

These results indicate that the developed coatings helped retain the desirable quality tomatoes during storage, which is important for maintaining appeal and market acceptability.

Table 3: Color characteristic of tomato coatings

Treatment	L* (0 d)	L* (20 d)	a* (0 d)	a* (20 d)	b* (0 d)	b* (20 d)	C* (0 d)	C* (20 d)	h° (0 d)	h° (20 d)
Control	32.83 ± 0.78^{bA}	32.04 ± 0.26^{aB}	20.62 ± 0.58^{cB}	22.47 ± 1.25^{bA}	14.24 ± 0.76^{bA}	13.69 ± 0.14^{bB}	25.07 ± 0.16^{cB}	26.32 ± 1.12^{bA}	55.36 ± 2.15^{cB}	58.62 ± 1.24^{bA}
T1	36.81 ± 1.13^{aA}	32.04 ± 1.31^{aB}	22.36 ± 1.17^{bA}	22.06 ± 0.36^{bB}	16.63 ± 0.90^{aA}	15.18 ± 0.65^{aB}	27.87 ± 1.47^{bA}	26.78 ± 0.32^{bB}	53.36 ± 0.19^{dB}	55.47 ± 1.46^{cA}
T2	31.91 ± 0.75^{cB}	32.04 ± 0.40^{aA}	18.96 ± 0.38^{dB}	20.46 ± 0.41^{cA}	12.66 ± 0.80^{cA}	12.55 ± 0.40^{cB}	22.80 ± 0.36^{dB}	24.01 ± 0.55^{cA}	56.25 ± 0.36^{bB}	58.48 ± 0.46^{bA}
T3	34.25 ± 0.10^{bA}	32.04 ± 0.28^{aB}	24.28 ± 0.43^{aA}	23.79 ± 1.24^{aB}	15.38 ± 0.27^{aA}	14.52 ± 0.28^{aB}	28.74 ± 0.51^{aA}	27.88 ± 1.10^{aB}	57.65 ± 0.01^{aB}	58.56 ± 1.29^{bA}
T4	32.97 ± 0.13^{bA}	32.04 ± 0.93^{aB}	21.17 ± 0.18^{cB}	21.93 ± 1.70^{bA}	13.39 ± 0.09^{bA}	13.04 ± 0.58^{bB}	25.05 ± 0.20^{cB}	25.52 ± 1.74^{cA}	57.69 ± 0.05^{aB}	59.22 ± 0.95^{aA}

Values are expressed as mean ± SD. Lowercase superscripts indicate descriptive ranking among treatments within each day (vertical comparison), while uppercase superscripts indicate descriptive ranking across storage days within each treatment (horizontal comparison).

Table 3a Color characteristic of tomato coatings

Treatment	BI (0 d)	BI (20 d)	ΔE* (0 d)	ΔE* (20 d)
Control	102.20 ± 5.90^{bA}	104.45 ± 3.29^{bA}	41.31 ± 0.64^{cA}	41.64 ± 0.72^{bA}
T1	103.96 ± 2.77^{bA}	102.16 ± 1.37^{cB}	46.17 ± 1.79^{aA}	44.07 ± 1.20^{aB}
T2	93.40 ± 1.76^{dB}	94.97 ± 1.63^{dA}	39.22 ± 0.78^{dB}	40.10 ± 0.63^{cA}
T3	109.68 ± 1.88^{aA}	105.28 ± 2.47^{aB}	44.71 ± 0.40^{bA}	43.95 ± 0.89^{aB}
T4	97.94 ± 1.04^{cB}	99.81 ± 3.06^{cA}	41.41 ± 0.14^{cA}	41.15 ± 1.80^{bA}

Values are expressed as mean ± SD. Lowercase superscripts indicate descriptive ranking among treatments within each day (vertical comparison), while uppercase superscripts indicate descriptive ranking across storage days within each treatment (horizontal comparison).

3.4 Ascorbic acid

The changes in ascorbic acid content of coated and without coated tomatoes during storage are shown in **Table 4**. In all treatments, a gradual decline in ascorbic acid levels was observed throughout storage period, reflecting the progressive loss of vitamin C as the fruits continued ripening during storage. The ascorbic acid content of the control tomatoes decreased from 7.21 to 5.40 mg/100g after 20 days of storage. Although a reduction was also noted in the coated tomatoes, the extent of the reduction varied among the different treatments. After 20 days of storage, T1 exhibited highest content of ascorbic acid (6.00 mg/100g). While the control and T3 maintained intermediate levels (5.40 mg/100g), whereas T4 showed the lowest ascorbic acid content at (4.80 mg/g). The observed reduction in ascorbic acid content is likely due to its oxidation into dehydroascorbic acid and further degradation during the ripening process. Since ascorbic acid is highly sensitive to oxygen, heat, and enzymatic processes, its content often decreases with increasing storage duration. The relatively high content of vitamin C in coated tomatoes may be attributed to the semi-permeable membranes of the edible coatings, which restricted oxygen exposure and reducing oxidative losses. Similar decreases in ascorbic acid content have been observed in coated tomatoes and other fruits during storage, where edible coatings helped preserve vitamin C by lowering respiration and moisture loss rates (Nasrin, Molla, Hossaen, Alam, & Yasmin, 2008; Pinheiro, Alegria, Abreu, Gonçalves, & Silva, 2013). The improved retention of ascorbic acid in coated tomatoes may be attributed to the slowing of ripening process, since ascorbic acid is actively utilized in many metabolic activities during fruit maturation. Moreover, the coatings containing encapsulated garlic extract may have enhanced extra protection against oxidative degradation through the antioxidant properties of its bioactive compounds. Similar findings have been reported by (Hernández-Muñoz, Almenar, Ocio, & Gavara, 2006), who observed that bioactive coatings were highly effective in preventing nutrient losses and preserving the nutritional integrity of the food products during storage.

These findings indicate that the coatings were effective in preserving ascorbic acid and maintaining the nutritional value of tomatoes during storage.

3.5 Lycopene content

The changes in lycopene content of coated and uncoated tomatoes during storage are shown in **Table 5.** The lycopene content gradually increased in all treatments during the storage period, ranging from about 29.28–29.33 mg/kg at day 0 to 29.60–29.63 mg/kg after 20 days of storage. At the end of storage, T4 recorded the highest lycopene content (29.63 mg/kg), while the control treatment showed the lowest value (29.60 mg/kg). The increase in lycopene content during storage indicates the continued ripening of tomatoes.

Table 4: Ascorbic acid content during storage.

Treatment	Day 0	Day 5	Day 10	Day 15	Day 20
Control	7.21 ± 0.10^{cA}	7.20 ± 0.11^{bA}	6.61 ± 0.11^{bB}	5.40 ± 0.10^{dc}	5.40 ± 0.10^{cc}
T1	7.20 ± 0.20^{cA}	6.60 ± 0.23^{cB}	6.60 ± 0.15^{bB}	6.00 ± 0.11^{bc}	6.00 ± 0.11^{bc}
T2	8.40 ± 0.05^{aA}	8.40 ± 0.05^{aA}	7.80 ± 0.15^{aB}	4.80 ± 0.20^{ec}	4.20 ± 0.23^{eD}
T3	7.80 ± 0.15^{bA}	7.20 ± 0.20^{bB}	6.60 ± 0.28^{bc}	6.00 ± 0.05^{bD}	5.40 ± 0.10^{cE}
T4	8.40 ± 0.11^{aA}	6.60 ± 0.15^{cB}	6.00 ± 0.20^{cc}	6.00 ± 0.15^{ac}	4.80 ± 0.05^{dD}

Values are expressed as mean ± SD. Lowercase superscripts indicate descriptive ranking among treatments within each day (vertical comparison), while uppercase superscripts indicate descriptive ranking across storage days within each treatment (horizontal comparison).

The increase in lycopene during storage is mainly associated with chloroplast-to-chromoplast transformation and enhanced carotenoid biosynthesis during ripening. The red color of tomatoes is mainly due to lycopene and its concentration generally increases as the fruit ripens. This increase in lycopene may result from the conversion of carotenoid precursors into lycopene together with the degradation of chlorophyll pigments during ripening. As tomatoes ripen, the chlorophyll gradually degrades and lycopene is synthesized, leading to the red color of ripe tomatoes. Thus, lycopene accumulation is an important sign of tomato ripening and contributes to the development of the characteristics red colour of the fruit. The slightly slower increase

in lycopene accumulation in coated tomatoes indicates that the edible coatings delayed the ripening process by decreasing gas exchange and respiration. Similar trends were reported by (Batu, 2004; Pinheiro et al., 2013), who reported a progressive increase in lycopene content during tomato storage and attributed carotenoid biosynthesis during ripening. Similarly, (A. Ali et al., 2010) reported that edible coatings delayed ripening-related metabolic changes while preserving the nutritional quality of tomatoes during storage. The relatively stable lycopene contents in coated tomatoes suggest that the developed coatings did not adversely interfere with lycopene formation and were effective to maintain the nutritional and visual quality of tomatoes during storage.

Table 5: Lycopene content of tomatoes during storage

Treatment	Day 0	Day 5	Day 10	Day 15	Day 20
Control	7.21 ± 0.10^{cA}	7.20 ± 0.11^{bA}	6.61 ± 0.11^{bB}	5.40 ± 0.10^{dc}	5.40 ± 0.10^{ec}
T1	7.20 ± 0.20^{cA}	6.60 ± 0.23^{cB}	6.60 ± 0.15^{bB}	6.00 ± 0.11^{bc}	6.00 ± 0.11^{bc}
T2	8.40 ± 0.05^{aA}	8.40 ± 0.05^{aA}	7.80 ± 0.15^{aB}	4.80 ± 0.20^{ec}	4.20 ± 0.23^{eD}
T3	7.80 ± 0.15^{bA}	7.20 ± 0.20^{bB}	6.60 ± 0.28^{bc}	6.00 ± 0.05^{bD}	5.40 ± 0.10^{cE}
T4	8.40 ± 0.11^{aA}	6.60 ± 0.15^{cB}	6.00 ± 0.20^{cc}	6.00 ± 0.15^{ac}	4.80 ± 0.05^{dD}

Values are expressed as mean ± SD. Lowercase superscripts indicate descriptive ranking among treatments within each day (vertical comparison), while uppercase superscripts indicate descriptive ranking across storage days within each treatment (horizontal comparison).

4. CONCLUSION

The present study successfully developed and applied a starch–gelatin edible coating incorporating bitter gourd seed protein nanoparticles for tomato preservation. The developed coatings significantly reduced the weight loss and delayed physicochemical changes, and ripening related changes, thereby helping to maintain fruit quality during the storage. The results showed that coated tomato retained higher titratable acidity and better color attributes compared with the uncoated tomatoes, while exhibited slower increase in pH, reflecting a decrease in metabolic deterioration during storage. Although the coatings did not markedly alter the natural changes in ascorbic acid and lycopene contents, they were effective in maintaining nutritional value and visual quality in tomatoes during the storage. The results demonstrated that the incorporation of encapsulated garlic extract increased the protective effect of the coating matrix and improving its efficiency to maintain fruit quality during ambient storage.

Overall, the developed coating system shows strong potential as a sustainable approach for extending tomato shelf life and preserves the market quality, while providing a valuable utilization of underexploited bitter gourd seed protein as a functional encapsulating material. This study highlights the potential of combining plant-based proteins with natural bioactive compounds in the development of active edible coatings for fresh produce preservation and provides a promising strategy for maintaining the postharvest quality of fresh fruits and vegetables.

CRediT authorship contribution statement

Tawseefa Jan: Investigation, Formal analysis, Data curation, Visualization, Writing – original draft, Writing – review & editing. **Naseer Ahmed**: Conceptualization, Supervision, Project administration, Funding acquisition, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests.

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Data availability

The data supporting the findings of this study are included within the article. Additional data related to this study are available from the corresponding author upon reasonable request.

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