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RESEARCH

Improvement in Physicochemical, Nutritional, and Microbial Stability of Tomatoes Using Gum Arabic-Based Composite Coating Functionalized with Keratin and Cinnamon Oil

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Abstract

In this study, we investigated the development of gum Arabic (GA)-based composite coatings functionalized with keratin (K) and cinnamon oil (CO) to enhance the physicochemical, nutritional, and microbial stability of tomatoes. Coating formulations containing GA-K-$CO_{0.1}$ (27:3:0.1, v/v/v) and GA-K-$CO_{0.5}$ (27:3:0.5, v/v/v) were developed and applied as coatings. Mature green tomatoes were treated with GA-K-$CO_{0.1}$ and GA-K-$CO_{0.5}$ and stored at 27.5 °C and 80.7% relative humidity (RH) for 20 days, with quality assessments at 5-day intervals. Formulations with a GA-K-$CO_{0.1}$ concentration extended the shelf life of tomatoes by up to 5 days under ambient conditions. This was achieved by significantly reducing weight loss by 31.9%, decay incidence by 33.3%, and exhibiting significant antifungal activity ($p<0.05$) compared with the uncoated control, which was coated with distilled water. The tomatoes coated with GA-K-$CO_{0.5}$ showed about a 6.21% retention in moisture content, total soluble solids, and a rise of roughly 60% in antioxidant capacity compared with control group. The formulation with a lower level of cinnamon oil in GA-K-$CO_{0.1}$ showed a significant ($p<0.05$) retention in β-carotene and lycopene levels, and further enhanced nutritional and visual quality, as well as its potential to inhibit bacterial and fungal growth. The gum Arabic-based coating functionalized with keratin and cinnamon oil presents a novel and sustainable method for postharvest tomato preservation, holding considerable promise to lower losses and improve food quality in supply chains.

Keywords Chicken feather waste · Gum arabic · Cinnamon oil · Postharvest storage

Introduction

Postharvest losses of fruits and vegetables remain a significant global challenge, with an estimated 15%–50% of harvested produce being lost annually due to inadequate storage and preservation systems [69]. Infrastructural limitations, poor handling practices, and unfavorable climatic conditions have intensified spoilage rates in developing countries [26, 95]. Losses of fresh produce in Sub-Saharan Africa vary from 40% to 60% after harvesting, mainly due to factors like microbial contamination, spoilage resulting from the produce's physiological condition, mechanical damage, and environmental stress factors including temperature and humidity [40, 81].

Tomato (*Solanum lycopersicum* L.) is a climacteric fruit of global economic and nutritional importance that is widely consumed both fresh and processed. Tomatoes contribute significantly to human health and dietary diversity owing to

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their rich antioxidants, such as lycopene, β-carotene, vitamin C, and phenolic compounds [94]. However, their high moisture content and metabolic activity make them highly susceptible to rapid spoilage during storage and distribution [9, 58]. In Nigeria, postharvest tomato losses are estimated at 50%, despite the country being one of the largest producers in Africa [96].

Natural, biodegradable coatings that can enhance the shelf life and maintain the quality of perishable crops are receiving increasing interest to mitigate these losses. Although conventional synthetic coatings are effective, their non-biodegradability and potential toxicity raise environmental concerns. Consequently, researchers are now investigating natural-based polymers and bioactive compounds as environmentally friendly alternatives [44, 70]. Promising properties have been identified in gum Arabic, a plant-derived polysaccharide, and keratin, derived from poultry waste, as well as in cinnamon oil, an essential oil with inherent antimicrobial and antioxidant properties, as studied by Ali et al. [5, 28] and Oluba et al. [61].

The bioactive components of cinnamon oil, such as cinnamaldehyde and eugenol, contribute to its broad-spectrum antimicrobial and antioxidant properties [42]. Studies have shown that incorporating it into edible coatings can impede microbial growth and slow down the spoilage process in fruits like strawberries and fresh-cut vegetables, as well as enhance their appeal through its distinctive aroma [32, 76].

In recent years, essential oils and plant extracts have gained substantial attention as natural additives in edible fruit coatings due to their multifunctional bioactive properties. These compounds are greatly prized for their potent antimicrobial and antioxidant characteristics, which are crucial in inhibiting microbial proliferation, slowing down oxidative spoilage, and maintaining the overall sensory and nutritional integrity of fruits during postharvest storage [15, 55]. Incorporating these bioactive agents into biopolymer matrices enhances both the physiological stability and shelf life of fruits [75], and offers a more environmentally friendly alternative to synthetic preservatives. Current research underscores their effectiveness in retarding decay, preserving texture, and boosting antioxidant capacity across a variety of fruit types, thereby advancing the development of active edible packaging technologies [6].

Cinnamon oil and similar oils have inherent limitations including volatility, heat sensitivity, susceptibility to oxidative degradation, and water insolubility; consequently, encapsulation or the use of carrier systems is necessary to enhance stability and facilitate controlled release [33, 35].

Gum Arabic, a naturally occurring polysaccharide, presents a promising medium for bioactive delivery matrices due to its emulsification, film formation, and biodegradability [79]. However, gum Arabic alone has a limited capacity for encapsulating monoterpenoid because of its relatively low hydrophobic affinity and structural porosity [12, 18, 62]. The addition of keratin, a fibrous, sulfur-rich biopolymer, to gum Arabic matrices introduces reactive functional groups such as thiols and amines and increases the matrix's mechanical strength and cohesiveness [63].

Thus, a composite of gum Arabic and keratin creates a semi-hydrophobic, biodegradable film that enhances the encapsulation efficiency and protective capabilities of volatile components, including cinnamaldehyde, a significant component of cinnamon oil, while additionally facilitating sustained release and environmental durability. Mukwevho et al. [56] demonstrated improved oxidative stability and microbial control of shelled temperate nuts using polysaccharide- and starch-based coatings. Consequently, the gum Arabic-keratin composite provides a functionally synergistic and sustainable platform for stabilizing cinnamon oil, enabling its effective use in postharvest tomato preservation through enhanced oxidative and microbial protection. This study seeks to develop and evaluate an innovative, edible film consisting of gum Arabic, keratin, and cinnamon oil to maintain the physical and chemical, nutritional, and microbial integrity of tomatoes during storage after they have been picked.

Materials and Methods

Materials

Chemicals and Reagents

All chemicals and reagents used in this study were of analytical grade including sulfuric acid, acetone, N-Hexane, 2,2-Diphenyl-1-picrichydrazyl (DPPH), ferric reducing antioxidant power reagent, Folin-Ciocalteu's reagent, sodium carbonate, sodium hydroxide, sodium thiosulphate and ammonium molybdate.

Chicken Feather

White-colored poultry feathers were sourced from the slaughter section of Obo Road Market in Ilorin, Kwara State, Nigeria. The feathers underwent a thorough cleaning process, initially washed with detergent and rinsed repeatedly under running water to eliminate residual blood, fats, and soap. Post-washing, the feathers were manually inspected and cleaned to remove extraneous materials such as skin, viscera, and beak remnants, and then spread on a clean, dry white surface for air drying. To ensure microbial

decontamination, the feathers were soaked in a 0.5% sodium hypochlorite solution for disinfection. Excess hypochlorite was neutralized using sodium thiosulfate, followed by repeated rinsing with distilled water to eliminate residual chemicals. The sanitized feathers were then dried to a constant weight at 60 °C in a hot air oven. After drying, the feathers were manually chopped into smaller fragments and milled into a fine powder using a mechanical grinder. The pulverized feather material was stored in airtight containers under dry conditions and kept for subsequent keratin extraction procedures.

Cinnamon

The cinnamon sticks were purchased from Kano, Kano state, Nigeria. The cinnamon sticks were milled into powdery form and kept for oil extraction.

Gum Arabic Source and Purification

Grade I Arabic gum crystals were sourced from Maiduguri, Borno state; the North Eastern part of Nigeria. Debris and other undesired particles were eliminated by sorting the entire Gum Arabic crystals. Following an overnight dissolution of the crystals in water, the resulting solution was filtered with muslin cloth to eliminate any remaining wood fragments and debris. The filtrate was thereafter concentrated in an air oven at 50 °C to remove any water present. The dried concentrated gum Arabic was milled to powder form using the hammer mill and the powder stored for further analysis.

Methods

Keratin Extraction

Keratin was obtained from chicken feather powder using alkaline hydrolysis [60, 64]. Then, 50 g of feather powder was immersed in 250 mL of 1 M NaOH and agitated for 8 h at 27 °C. The resulting hydrolysate was filtered, and the pH was adjusted to neutral using 2% glacial acetic acid to induce keratin precipitation. The precipitate was washed with distilled water, dried at 50 °C, ground, and sieved (50 µm) before refrigeration at 4 °C.

Extraction of Cinnamon Oil

To extract oil from cinnamon, hydrodistillation was conducted using a Clevenger apparatus. A 100-g aliquot of cinnamon powder was placed in a round-bottom flask with enough water to submerge the material. The setup was heated for 1 h, allowing the essential oil to vaporize with steam and condense into a distinct oil-water layer. The oil layer was collected in amber vials for subsequent use [17].

Formulation of Gum Arabic-keratin Biocomposite Functionalized with Cinnamon Oil

To prepare the coating medium, keratin was solubilized in 0.1 M NaOH and gum Arabic was dissolved in distilled water. Glycerol served as the plasticizer. Cinnamon oil was added according to the formulation matrix (Table 1), and the mixture was stirred using a magnetic stirrer at 40 °C for 1 h [60, 64].

Coating Application

Tomatoes were immersed in respective formulations for 2 min to achieve uniform coating. Control samples were immersed in distilled water. All samples were air-dried and stored in cartons at ambient temperature. Quality assessments were conducted at 5-day intervals over 20 days.

Estimation of Weight Loss and Decay Incidence Weight loss was assessed by measuring the sample mass using a digital balance (Snowrex Electronic Scale 56503238, London). The percentage loss was calculated using Eq. (1).

$$\text{Weight loss } (\%) = \frac{\text{Initial weight} - \text{Final weight}}{\text{Initial weight}} \times 100 \quad (1)$$

Decay incidence was assessed by counting the number of spoiled fruits at the end of the storage period for each treatment group [20], and the results were expressed as a percentage using Eq. (2).

$$\text{Decay incidence } (\%) = \frac{\text{Number of Decayed fruits}}{\text{Total number of fruits}} \times 10 \quad (2)$$

Determination of Moisture Content Moisture content was determined following the AOAC [8] protocol. Briefly 2 g of homogenized tomato sample was oven-dried at 130 °C for

Table 1 Preparation of coating media using gum Arabic, keratin, cinnamon oil and glycerol

Groupings	Gum Arabic (15%) (mL)	Keratin (5%) (mL)	Cinnamon oil (100%) (mL)	Glycerol (mL)
A	27	3	0.5	3
B	27	3	0.1	3
C	27	3	0	3
D	30	0	0	3
E	0	30	0	3
F	0	0	0	0

one hour until a constant weight was achieved. The moisture content was then calculated using Eq. (3).

$$Moisture\ content\ (\%) = \frac{W_0 - W_1) - W_2}{W_0} \times 100 \quad (3)$$

Where: W_0 = weight of sample, W_1 = weight of empty can and W_2 = weight of can + sample after drying.

Determination of Ash Content Ash content was determined according to the AOAC [8] method. A 2 g portion of pulverized sample was incinerated in a muffle furnace at 600 °C for 4 h until a constant weight was obtained. The ash content was calculated using Eq. (4).

$$Ash\ content\ (\%) = \frac{W_2 - W_0}{W_1 - W_0} \times 100 \quad (4)$$

Where; W_0 = weight of empty crucible, W_1 = weight of crucible + sample (before blasting), W_2 = weight of crucible + ash (after blasting).

Measurement of pH, Titratable Acidity (TTA) (%) and Total Soluble Solid (TSS) The pH, titratable acidity, and total soluble solids were measured in accordance with AOAC [8] procedures. A 10 g portion of the tomato sample was homogenized in 100 mL of distilled water and centrifuged at 5000 × g for 20 min at 4 °C. The resulting supernatant was used for all analyses. pH was measured at 20 °C using a calibrated pH meter. Titratable acidity was assessed by titrating the supernatant with 0.1 N NaOH to an endpoint pH of 8.1, indicated by a rose-pink color. Total soluble solids were determined at 20 °C using a refractometer and expressed in °Brix.

Estimation of sugar-acid Ratio Sugar-acid ratio was determined from the TSS and TTA of the tomato fruits (as ripening index) by calculating the TSS divided by TTA.

Determination Total of Phenolics Total phenolic content was quantified using the Folin–Ciocalteu method, with slight modifications from the protocol described by Ali et al. [5]. Briefly, 0.1 mL of the homogenized tomato sample was combined with 0.5 mL of Folin-Ciocalteu reagent and 1.5 mL of 7% sodium carbonate solution. The mixture was then diluted with distilled water to a final volume of 10 mL and incubated at 40 °C for 2 h. Absorbance was measured at 750 nm using a UV-VIS spectrophotometer (Varioskan Flash Multimode Reader, Thermo Fisher Scientific, USA). Results were expressed as milligrams of gallic acid equivalents (GAE) per 100 g of fresh coating medium.

Carotenoids Determination Carotenoids were extracted by mixing 1 g of homogenized tomato sample with 16 mL of an acetone–hexane mixture (4:6 v/v) in a test tube. After thorough mixing, the solution was allowed to separate into two phases, and an aliquot was taken from the upper layer. The optical density (OD) of this aliquot was measured at 663, 645, 505, and 453 nm using a UV-VIS spectrophotometer. Lycopene and β-carotene concentrations were calculated using the equations reported by Nagata and Yamashita [57] as referenced by Sharoba [78] and presented in Eqs. (5) and (6).

$$\begin{aligned} &Lycopene\ \left(\tfrac{mg}{100}mL\right) \\ &= -0.0458 \times OD_{663} + 0.204 \\ &\times OD_{645} + 0.372 \times OD_{505} \\ &-0.0806 \times OD_{453} \end{aligned} \quad (5)$$

$$\begin{aligned} &Beta\ carotene\ \left(\tfrac{mg}{100}mL\right) \\ &= 0.216 \times OD_{663} - 1.22 \\ &\times OD_{645} - 0.304 \times OD_{505} \\ &+0.452 \times OD_{453} \end{aligned} \quad (6)$$

Where OD = optical density.

Determination of Vitamin C Content Ascorbic acid content was determined using a modified version of the 2,6-dichlorophenol indophenol (DCPIP) titration method outlined by AOAC [8]. Briefly, 2 g of homogenized tomato sample was extracted in a mortar with 10 mL of 0.5% oxalic acid solution. The mixture was transferred into a 100 mL volumetric flask and diluted to volume with the same extraction solution. After thorough mixing, the solution was immediately filtered using Whatman No. 4 filter paper. A 10 mL aliquot of the filtrate was titrated against a standardized DCPIP solution, while a blank titration was performed simultaneously using the extraction solvent alone.

Determination of Antioxidant Activities Ferric Reducing Antioxidant Power (FRAP) assay

The total antioxidant capacity of stored tomatoes was evaluated using the Ferric Reducing Antioxidant Power (FRAP) assay, following the method described by Liaqat et al. [47]. The assay reaction mixture included 20 µL of tomato juice sample, 150 µL of FRAP reagent, 20 µL of ascorbic acid as the positive control, and 20 µL of distilled water as the blank. Absorbance was measured at 593 nm using a UV-VIS spectrophotometer (Varioskan Flash Multimode Reader, Thermo Fisher Scientific, USA). Antioxidant activity was then calculated using Eq. (7).

$$FRAP\ value = (A_1 - A_0)/(A_c - A_0) \times 2 \quad (7)$$

Where: A_c is the absorbance of the positive control,
A_1 is the absorbance of the sample, and.
A_0 is the absorbance of the blank.

DPPH Assay

The antioxidant potential of tomato juice was further evaluated using the DPPH (1,1-diphenyl-2-picrylhydrazyl) radical scavenging assay, adapted from the protocol described by Lim and Quah [48] and cited by Maswada [51] with slight modifications. A 0.15 mM DPPH solution was freshly prepared in 100% methanol. In the assay, 1 mL of tomato juice was combined with 2 mL of the DPPH solution and allowed to react at ambient temperature for 30 min. Absorbance was measured at 517 nm using a UV-VIS spectrophotometer (Varioskan Flash Multimode Reader, Thermo Fisher Scientific, USA). A blank solution, consisting of 1 mL methanol and 2 mL DPPH, was included for baseline correction. The radical scavenging activity was calculated and expressed as a percentage inhibition using Eq. (8).

$$Radical\ scavenging\ activity\ (\%) = 1 - \frac{A_{sample}}{A_{blank}x}\,10 \qquad (8)$$

Where A is absorbance at 517 nm.

Sensory Evaluation Sensory assessment of the stored tomato samples was conducted after 28 days of storage. A panel of 20 untrained individuals, familiar with tomato quality based on routine consumer experience, was engaged to evaluate sensory attributes including color, appearance, odor, firmness, and overall acceptability. The evaluation was performed using a five-point hedonic scale (straightforward and easy to understand by untrained panels), following the method described by Larmond [46].

Microbial Analysis Source of Microbial Agent

Clinical isolates of the pathogenic microorganisms *Staphylococcus aureus* and *Escherichia coli* were obtained from the Medical Microbiology and Parasitology Laboratory at the University of Ilorin Teaching Hospital, Ilorin, Kwara State. Spoilage fungi, specifically *Aspergillus flavus* and *Penicillium* species, were sourced from the Microbiology Laboratory of the Nigerian Stored Products Research Institute, Ilorin. All test organisms used for the antimicrobial assays were maintained at 4 °C on appropriate nutrient agar and potato dextrose agar slants. Standardization of the bacterial and fungal inocula was achieved using the 0.5 McFarland turbidity standard (equivalent to 1.5×10^8 CFU/mL) and hemocytometer-based spore count (1.0×10^6 CFU/mL), respectively.

Preparation of Culture Media

Preparation of nutrient agar (NA), potato dextrose agar (PDA), and other culture media followed standard procedures as described in AOAC [8] and Cheesbrough [13]. Media were prepared according to manufacturer guidelines and sterilized by autoclaving at 121 °C for 15 min [30].

Sterility Testing of the Coating Medium

To assess the sterility of the coating formulations labeled A, B, C, D, and E, as well as the control sample (F, containing distilled water), each sample was aseptically dispensed into sterile Petri dishes. Using the pour plate method, pre-prepared and autoclaved Nutrient Agar and Potato Dextrose Agar were poured into the dishes containing the respective coating samples, gently mixed, and allowed to solidify under aseptic conditions. For bacterial evaluation, plates were inverted and incubated at 37 °C for 24–48 h, whereas fungal plates were incubated at 28 °C for 24–72 h. Following incubation, microbial growth was assessed by enumerating colony-forming units (CFU) using a digital colony counter. Results were recorded as the number of bacterial or fungal colonies per milliliter of sample, and instances of no microbial growth were also documented.

Enumeration of Bacteria

Bacterial enumeration was carried out following the method outlined by Cheesbrough [13]. Precisely 1 g of each sample was aseptically introduced into 9 mL of sterile distilled water to obtain a 10^{-1} dilution. The mixture was thoroughly agitated, and 1 mL from this dilution was transferred into a second tube containing 9 mL of sterile distilled water to achieve a 10^{-2} dilution. This serial dilution process continued until a 10^{-5} dilution was obtained. The 10^{-2} and 10^{-4} dilutions were selected for bacterial enumeration using the pour plate method with nutrient agar. Each dilution was plated in duplicate. The plates were inverted and incubated at 35 °C for 24–48 h. After incubation, colony-forming units (CFU) were counted using a colony counter, and bacterial counts were recorded as mean CFU/mL. Isolated colonies were further purified by repeated streaking on nutrient agar to obtain pure cultures, which were subsequently maintained on agar slants and stored at 4 °C for further analysis.

Enumeration of Fungi

Fungal enumeration was conducted using the method described by Cheesbrough [13]. One gram (1 g) of each sample was aseptically transferred into 9 mL of sterile distilled water to produce a 10^{-1} dilution. The tube was thoroughly mixed, and 1 mL of this dilution was then transferred into another 9 mL of sterile distilled water to achieve a 10^{-2} dilution. This serial dilution process continued until a 10^{-5} dilution was obtained. From the 10^{-1} and 10^{-3} dilutions, 1 mL aliquots were used to determine the total fungal count by the pour plate method using potato dextrose agar (PDA). Each sample was analyzed in triplicate. The inoculated plates were incubated at 28 °C for three days. After incubation, visible colonies were counted using a colony counter, and the results were expressed as mean colony-forming units per

milliliter (CFU/mL). Representative colonies were isolated and purified by repeated subculturing on PDA to obtain pure fungal cultures, which were subsequently maintained on PDA slants and stored at 4 °C for further analysis.

Antimicrobial Effectiveness Testing Using Disc Diffusion Method

The antimicrobial efficacy of the coating medium was evaluated using the agar well diffusion technique on Mueller Hinton Agar, following the method described by Shrestha [80]. Standardized microbial inocula were evenly spread onto the surface of the agar plates, after which 50 µL of each test extract was aseptically introduced into pre-bored wells. For bacterial strains, the plates were incubated at 35 ± 2 °C for 24 h, while fungal assays were incubated at 30 ± 5 °C for 72 h. Following incubation, the diameter and clarity of the zones of inhibition surrounding each well were measured to assess antimicrobial activity.

To ensure reproducibility and reliability of the antimicrobial efficacy results, all assays were conducted in triplicate for each test organism. Each bacterial and fungal strain was tested using three independent replicates, and the average zone of inhibition diameters along with standard deviations were reported accordingly.

Gas chromatography–mass Spectrometry (GC–MS) Analysis

The chemical composition of cinnamon oil was analyzed using capillary gas chromatography–mass spectrometry (GC–MS). Analyses were conducted on a Shimadzu GCMS-QP2010 system, equipped with a flame ionization detector (FID) and a fused silica capillary column (OPTIMA XLB; 60 m × 0.25 mm i.d., 0.25 µm film thickness). The injector and detector temperatures were maintained at 270 °C and 300 °C, respectively. Compound separation was achieved via gas chromatography, while structural identification of eluted constituents was performed using a Shimadzu GCMS-QP2010 mass spectrometry detector, integrated with the same chromatographic system. This setup allowed for precise qualitative and semi-quantitative profiling of volatile and semi-volatile constituents in the test samples.

Statistical Analysis

Data were analyzed using a completely randomized design (CRD), with each treatment conducted in triplicate. Statistical analysis was performed using one-way analysis of variance (ANOVA) in SPSS v20.0. Differences between treatment means were compared using Duncan's Multiple Range Test (DMRT) at a significance threshold of $p < 0.05$. Results are presented as mean values ± standard deviation (SD).

Results and Discussion

Effect on Weight Loss

The impact of GA, K, and CO coatings on the weight loss percentage of stored tomatoes is presented in Fig. 1a. The recorded weight loss ranged from 12.407% to 18.214%, with the control group (F) exhibiting the highest weight loss (18.214%), followed by group E (keratin alone) with 14.864%. In contrast, group B (GA-K-$CO_{0.1}$) demonstrated the lowest weight loss percentage (12.407%), indicating superior effectiveness in reducing postharvest weight loss. Weight loss is a critical determinant of tomato quality and marketability [9]. According to Felicia et al. [31] the properties and impact of the coating material influence weight loss, particularly its ability to form a protective barrier that reduces transpiration and respiration rates. The treated groups showed a lower level of weight loss compared to the control group, suggesting that the coatings limited water loss and gaseous exchange, thereby enhancing postharvest storage stability [29]. Furthermore, a lower concentration of cinnamon oil in gum Arabic-keratin resulted in a substantial reduction in weight loss, demonstrating its potential as a biodegradable postharvest preservation method. Coatings based on pectin result in reduced weight loss in avocados [49], while keratin-starch coatings achieve the same outcome in tomato fruits [61]. These results collectively show the effectiveness of biopolymeric coatings in maintaining quality and prolonging the shelf life of perishable agricultural products.

Effect on Incidence of Decay

The decay incidence of the treated and control groups is illustrated in Fig. 1b, with values ranging from 11.429% to 28.571%. Group E, consisting of keratin alone, had the highest degeneration rate (28.571%), whereas Group B, containing GA-K-$CO_{0.1}$, had the lowest degeneration rate (11.429.s. The decay incidence in the control group was 17.142%, further emphasizing the limitation of keratin alone as a protective coating. Keratin alone does not provide sufficient antimicrobial protection, allowing microbial colonization and spoilage, ultimately shortening the shelf life of stored tomatoes [41]. Groups A (GA-K-$CO_{0.5}$) and B (GA-K-$CO_{0.1}$) exhibited a significantly lower rate of decay, supporting the antimicrobial properties of cinnamon oil, as observed Bohme et al. [11] and Sienkiewicz et al. [82]. This study's results also support those of Sarengaowa et al. [76], who discovered that adding cinnamon oil to coatings for fresh-cut fruits and vegetables effectively prevented microbial growth, thereby reducing decay. This study provides further evidence on the efficacy of gum Arabic-keratin-cinnamon

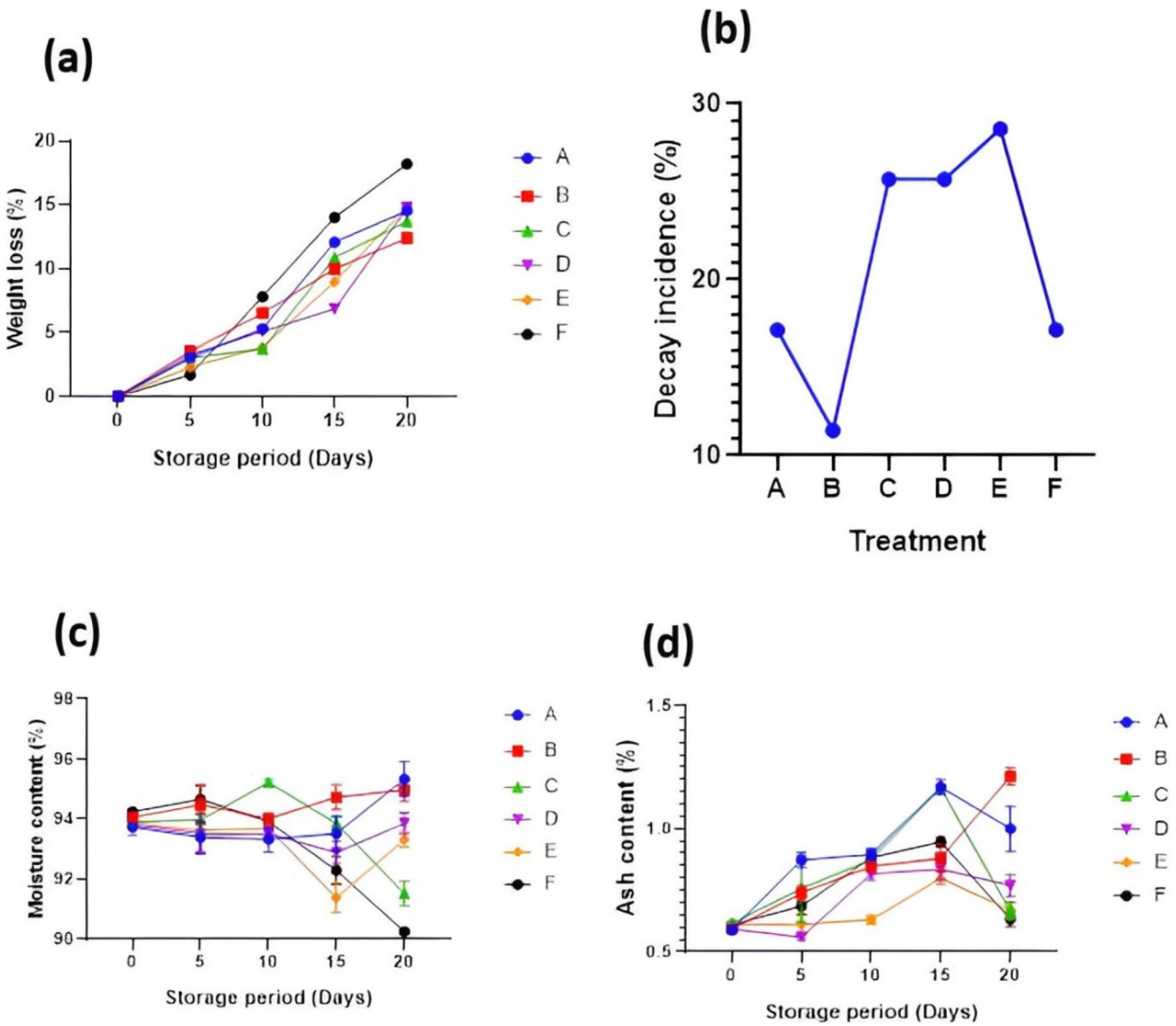

Fig. 1 Effect of gum Arabic (GA), keratin (K) and cinnamon oil (CO) treatment on (**a**) percentage weight loss (%), (**b**) decay incidence (%), (**c**) Ash, and (**d**) moisture content of stored tomato. Data are means ± SD of three determinations. Note: A, GA-K-$CO_{0.5}$ (27:3:0.5); B, GA-K-$CO_{0.1}$ (27:3:0.1); C, GA-K (27:3); D, GA (15% w/v); E, keratin (5% w/v); F = Control (distilled water)

oil coatings in extending shelf life in agricultural produce by preventing microbial deterioration.

Effect on Moisture Content

The moisture content of both treated and control groups over the storage period is presented in Fig. 1c, with values ranging between 90.28% and 95.92%. On day 20, the control group (F) exhibited the lowest moisture content (90.28%), which was significantly lower ($p < 0.05$) than that of all treated groups. In contrast, group A (GA-K-$CO_{0.5}$) retained the highest moisture content, followed by group B (GA-K-$CO_{0.1}$), which exhibited superior water retention properties. On day 20, no substantial variation was noted between groups D (gum Arabic) and E (keratin), suggesting that although these coatings offered some moisture retention, their efficacy might be improved when combined with other functional components. A key characteristic of edible coatings is their ability to reduce transpiration and respiration rates, thereby minimizing moisture loss and preserving fruit quality [59, 74]. In this study, all coated groups retained higher moisture levels than the control, reinforcing the role of biopolymer-based coatings in delaying dehydration. These findings are consistent with those of previous

studies. Studies by Abebe et al. [1] and Peralta-Ruiz et al. [67] showed that pectin- and chitosan-based coatings significantly reduced moisture loss in tomatoes, while Ruelas-Chacon [72] found equivalent water retention benefits from gellan gum and chitosan coatings. This study further confirms the efficacy of gum Arabic-keratin-cinnamon oil coatings in reducing moisture loss, thereby extending the shelf life of fresh tomatoes.

Effect on Ash Content

The changes in ash content of both treated and control groups over the 20-day storage period are presented in Fig. 1d, with values ranging between 0.59% and 1.25%. In groups A (GA-K-$CO_{0.5}$), C (GAK), and E (keratin), the ash content increased until day 15, after which it decreased. On the other hand, group B (GA-K-$CO_{0.1}$) reached its highest ash content on day 20, substantially exceeding that of the other treated and control groups. Ash content is a crucial indicator of nutritional quality and provides insights into the essential mineral composition of stored tomatoes [53]. The high ash content in groups A, B, and C implies that the combined effect of gum Arabic, keratin, and cinnamon oil resulted in enhanced mineral retention, which ultimately enhanced the nutritional value of the stored tomatoes. These findings are consistent with those of Sultana et al. [85] who demonstrated that chitosan-based coatings helped retain calcium and magnesium in tomatoes. Similarly, Abebe et al. [1] highlighted that reduced moisture loss leads to a higher mineral concentration, further supporting the results of this study. A 2022 study by Rather et al. found that tomatoes treated with gelatin retained significantly more ash during storage than the control group, which demonstrates the advantages of using bio-based coatings to maintain mineral content and post-harvest quality.

Effect on Total Titratable Acidity

The observed decline in titratable acidity (TTA) Fig 2a may be due to the conversion of organic acids into sugars and other metabolic compounds as the fruit ripens from green to red [38]. Notably, TTA levels were significantly higher in groups A (GA-K-$CO_{0.5}$), B (GA-K-$CO_{0.1}$), C (GA-K), and D (gum Arabic) than in groups E (keratin alone) and the control group F. This suggests that gum Arabic, keratin, and cinnamon oil coatings may slow the ripening process, thereby delaying acid degradation and extending the postharvest life of tomatoes. The results are consistent with those of Martinez-Romero [50] and Iqbal et al. [38] who found that applying Aloe vera and chitosan-ZnO nanoparticles to sweet cherries and tomatoes, respectively, resulted in a decrease in TTA and highlighted the potential of edible coatings to influence organic acid metabolism and extend the shelf life of fruit.

Effect on Total Soluble Sugar

The effect of GA, K, and CO coatings on the TTS content of stored tomatoes is presented in Fig. 2b, with values varying from 2.83 to 5.83 Brix°. A significant ($p<0.05$) increase in TSS levels was observed in both the treated and control groups up to day 5, after which group D exhibited a notable decline as storage progressed to day 20. Groups A, B, and C exhibited a steady increase in TSS throughout the experimental period, indicating extended ripening control and sugar retention. The control group, F, recorded the highest TSS value on day 15, suggesting that the untreated tomatoes reached peak ripeness at this point. TSS is a key indicator of fruit sweetness, flavor, and overall nutritional quality, which influences consumer acceptability and market value [34]. The increase in TSS levels during ripening can be attributed to the conversion of starches into sugars, with higher readings indicating greater sugar accumulation [39, 88]. This study findings align with the work of Shakir et al. [77] and Quabbaj and Daraghmah [71] which indicated that coating tomatoes with a combination of Gum Arabic and guar gum yielded higher TSS values compared to uncoated controls, ultimately resulting in longer shelf life and improved fruit quality. Additionally, Eidangbe and Oluba [25] demonstrated that keratin-starch coatings infused with avocado peel polyphenols effectively preserved higher TSS levels in tomatoes than uncoated samples. These findings reinforce the role of biopolymer-based coatings in delaying sugar degradation and extending fruit freshness.

Effect on Brix-acid Ratio

The impact of incorporating gum Arabic, keratin, and cinnamon oil on the sugar Brix-acid ratio of tomatoes is presented in Fig. 2c. The Brix-acid ratio across all groups, including the control and treated samples, ranged from 15.34 to 51.39. Although no significant differences were observed in the Brix-acid ratio at day 0, a notable increase was recorded in all groups as the storage period progressed to day 10. On day 20, GA-K-$CO_{0.1}$ (Group B) exhibited the highest Brix-acid ratio, with a statistically significant difference compared with the other groups. The elevated Brix-acid ratio in Groups B, C, D, and E may be attributed to gum Arabic and keratin's ability to reduce moisture loss in the fruit. The Brix-acid ratio serves as a crucial indicator of fruit quality, representing the balance between sweetness and acidity that has a significant impact on the overall flavor profile of tomatoes [7]. A higher Brix-acid ratio typically corresponds to a sweeter taste due to an optimal balance between sugar content and acidity [68, 90]. Research has also found that a higher Brix-acid ratio is linked to a longer shelf life in tomatoes as this ratio allows for the preservation of both flavor and moisture levels [49, 90]. This study's results agree with

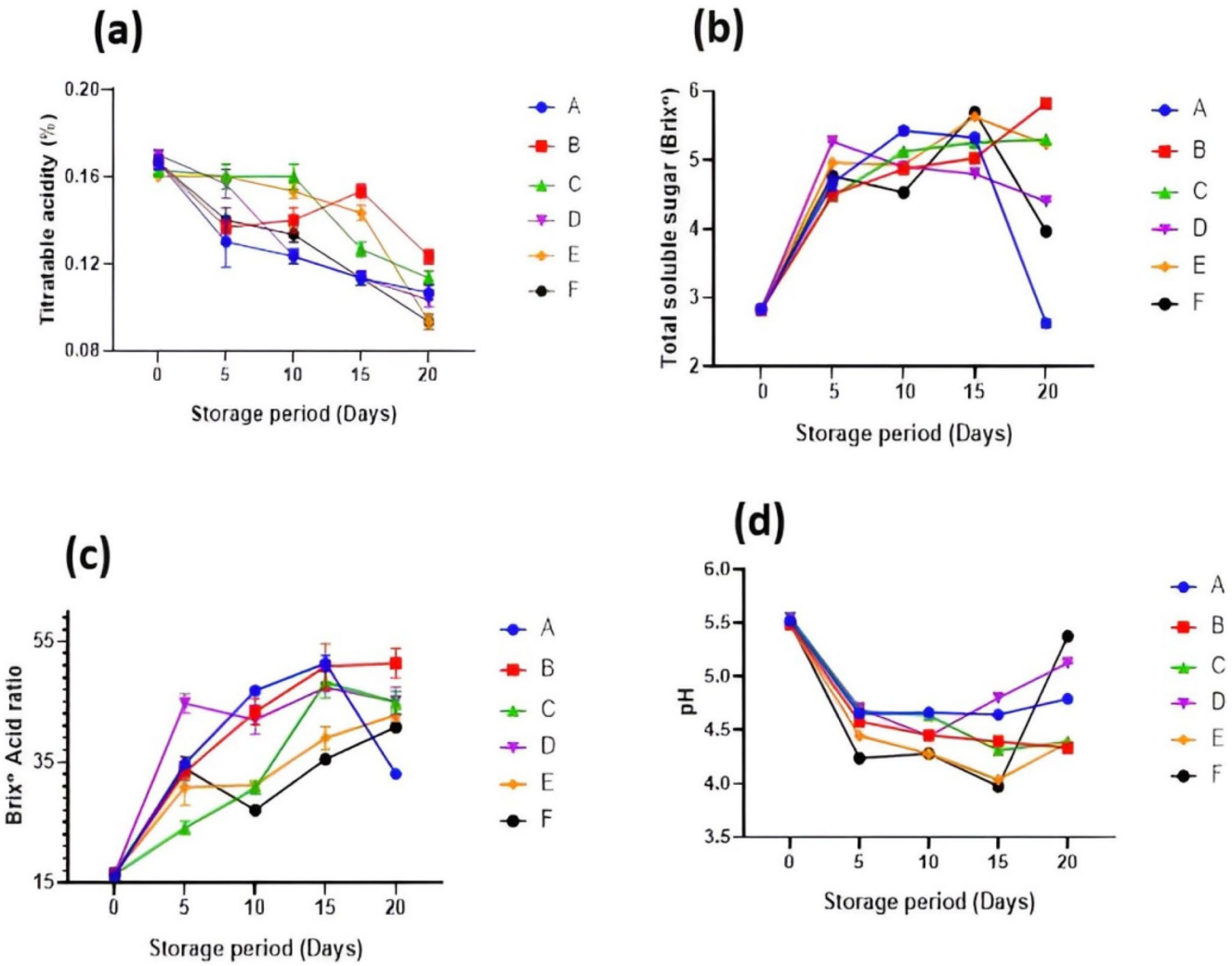

Fig. 2 Effect of gum Arabic (GA), keratin (K) and cinnamon oil (CO) treatment on (**a**) total titratable acidity (%), (**b**) total soluble sugar (Brix°), (**c**) pH, and (**d**) Brix° acid ratio of stored green tomato. Data are means ± SD of three determinations. Note: A, GA-K-$CO_{0.5}$ (27:3:0.5); B, GA-K-$CO_{0.1}$ (27:3:0.1); C, GA-K (27:3); D, GA (15% w/v); E, keratin (5% w/v); F = Control (distilled water)

Umeohia and Olapade's [90] findings, which showed that edible coatings improve flavour retention and extend the shelf life of tomatoes by maintaining an optimal Brix-acid ratio. These results reinforce the potential of coating treatments in postharvest management strategies for improving tomato quality and storage longevity.

Effect on pH Change

The pH values of the tomato samples ranged from 4.04 to 5.5 (Fig. 2d), with the initial sample having the highest value. A significant decrease in pH was observed as the storage period progressed. However, a notable increase occurred in Groups A and D on day 15 and in Groups A, D, and F on day 20, exceeding the acceptable pH range for ripe tomatoes (4.0–4.6). Raising the pH beyond this range makes produce more susceptible to microbial assault and disintegration [54]. Normally, tomatoes' pH levels fall as they ripen, due to the metabolic conversion of organic acids, like citric and malic acids, into sugars and other compounds [37]. The study's results align with those of Tiamiyu et al. [89] which found that coatings based on gum Arabic can delay a decrease in tomato acidity, potentially leading to improved postharvest quality and a longer shelf life.

Effect on Total Phenolic Content

The effect of incorporating gum Arabic, keratin, and cinnamon oil on the total phenolic content (TPC) and vitamin C levels in stored tomatoes is presented in Fig. 3a. The TPC varied between 4.58 and 13.65 mg/100 mL. A significant increase in TPC was observed in both the treated and

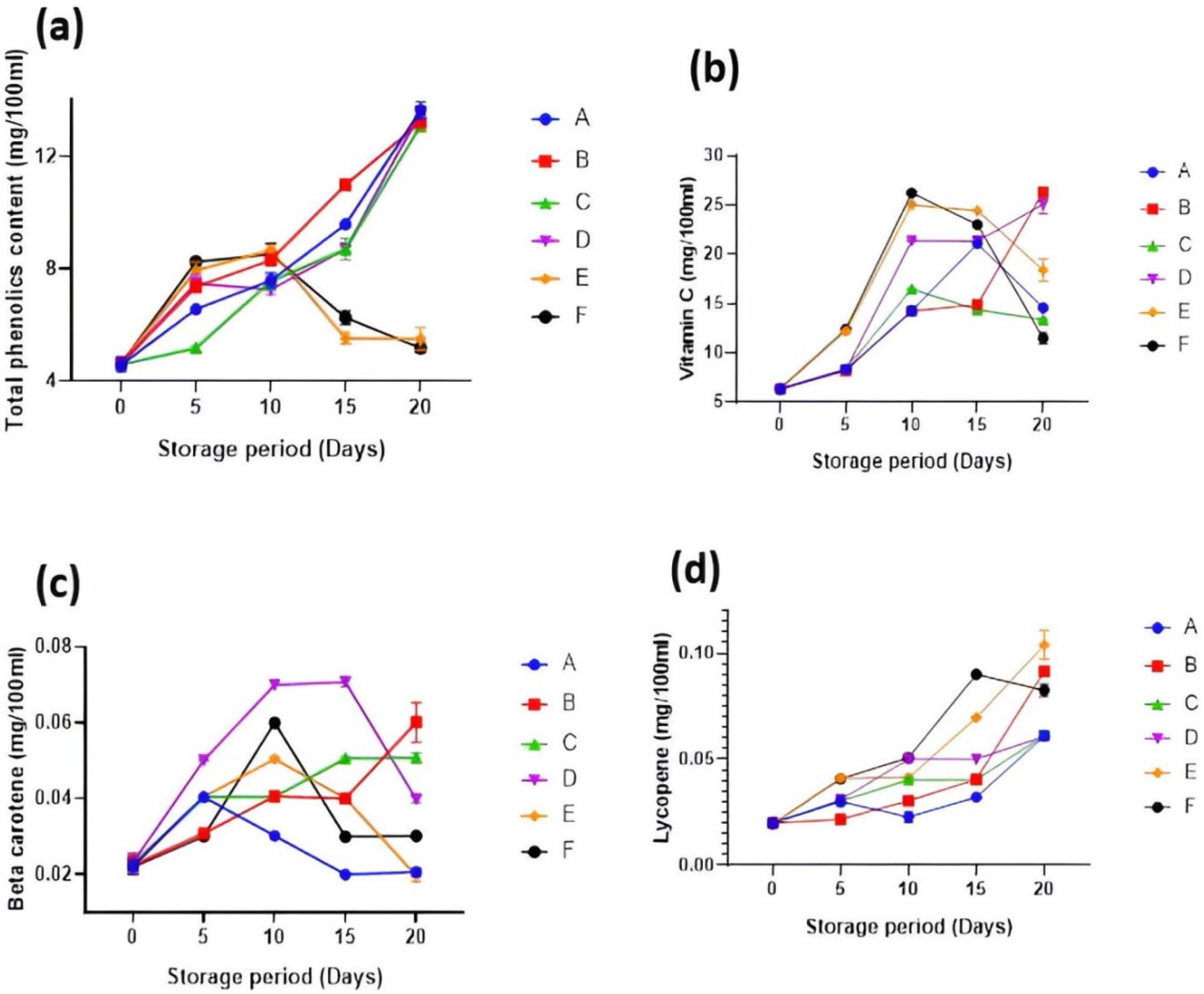

Fig. 3 Effect of Gum Arabic (GA), Keratin (K) and Cinnamon oil (CO) treatment on the (**a**) total phenolics content, (**b**) vitamin C content, (**c**) Beta carotene, and (**d**) lycopene content of stored tomato. Data are means ± SD of three determinations. Note: A, GA-K-$CO_{0.5}$ (27:3:0.5); B, GA-K-$CO_{0.1}$ (27:3:0.1); C, GA-K (27:3); D, GA (15% w/v); E, keratin (5% w/v); F = Control (distilled water)

control groups as storage progressed. A substantial decline in TPC was noted in Groups E and F on days 15 and 20, primarily resulting from keratin's improved efficacy when combined with other biomolecules, as opposed to its use alone [22]. The increase in TPC observed in Groups A and B may be linked to the high phenolic content of cinnamon oil [43]. According to Venkatachalam [92] coatings combining chitosan and cinnamon oil extend the shelf life of fruits and vegetables and enhance TPC. Furthermore, the rise in TPC in Groups C and D supports the hypothesis of Pan et al. [65] that coatings derived from gum Arabic increase the phenolic content in fruits either by halting the degradation of these compounds during storage or by creating an environment that encourages their metabolic activity, resulting in a larger amount of phenolic compounds.

Effect on Vitamin C Content

The effect of incorporating gum Arabic, keratin, and cinnamon oil on the vitamin C content of coated tomatoes is presented in Fig. 3b. The vitamin C content ranged from 6.18 to 26.17 mg/100 g. During storage, an overall rise in vitamin C content was observed, yet no substantial variation was found among Groups A, B, C, and D, nor was any significant difference ($p > 0.05$) observed among these groups. Likewise, no considerable difference ($p > 0.05$) was noted among Groups E and F on day 5. Starting from day 15, vitamin C levels decreased in Groups E and F, persisting through day 20, with Group F displaying the lowest concentration of 12.2 mg/100 g, which was substantially lower than the values in the treated groups. Vitamin C, a potent

antioxidant, plays a crucial role in protecting cells from oxidative stress by scavenging free radicals, which otherwise contribute to senescence and deterioration during storage. Its reduction increases the fruit's susceptibility to physical damage, bacterial growth, and fungal infections, all of which can accelerate spoilage [84]. The decline in vitamin C content in Groups E and F suggests that keratin-based coatings perform more effectively when combined with other biomolecules. Previous studies conducted by Ali et al. [5] and Taher et al. [87] have shown that tomatoes coated with gum Arabic contain higher levels of vitamin C compared to uncoated samples throughout storage. This study corroborates Enidiok et al. [27] findings, which showed that keratin-starch coatings with chia oil retarded vitamin C degradation in tomatoes stored at room temperature, in comparison with uncoated tomatoes.

Effect on β-carotene and Lycopene Content

The β-carotene content of stored tomatoes ranged from 0.02 to 0.07 mg/100 mL (Fig. 3c), and a significant increase was observed up to day 5 across almost all groups except Group B (GA-K-$CO_{0.1}$). A decline in β-carotene was noted by day 15 in Groups A (GA-K-$CO_{0.5}$), E (keratin alone), and F (control), indicating that coatings containing keratin and higher concentrations of gum Arabic-keratin-cinnamon oil (0.5) effectively prevent degradation only for about 10 days. In contrast, Groups B (GA-K-$CO_{0.1}$) and C (GA-K) maintained or increased β-carotene throughout storage, suggesting better chlorophyll preservation and delayed ripening. Lycopene content ranged from 0.02 to 0.1 mg/100 mL (Fig. 3d), with no significant declines in treated groups. Group E (keratin alone) showed the highest lycopene levels, comparable to Group B, indicating keratin's role in microbial growth retardation and moisture retention. The synergy between gum Arabic, keratin, and cinnamon oil in Group B likely enhanced antimicrobial and mechanical barrier properties, reducing nutrient loss. Carotenoid degradation, notably β-carotene and lycopene, was observed in gum Arabic-keratin composite coatings containing higher cinnamon oil concentrations. This is mainly attributed to the reactive aldehyde characteristics of cinnamaldehyde (a major constituent of cinnamon oil) and other volatile compounds. Compounds of this kind can trigger oxidative reactions through the generation of reactive oxygen species, which enables lipid peroxidation, resulting in damage to carotenoid molecules prone to oxidation, heat, and light exposure [86] Meng et al. [52]. High levels of cinnamon oil can also damage cellular membranes, resulting in an imbalance of antioxidants within the tomato tissue and a heightened risk that carotenoids will degrade during storage [92]. While cinnamon oil enhances microbial stability and suppresses spoilage, these oxidative interactions necessitate careful coating formulation optimization to balance effective preservation with nutrient retention. Gum Arabic-keratin matrix helps stabilize cinnamon oil against photodegradation and oxidative loss, but excessive bioactive concentration risks nutrient compromise. This trade-off underscores the importance of tailoring essential oil concentration to maintain tomato quality and health benefits in postharvest management. These findings corroborate prior studies indicating that gum Arabic-based coatings extend tomato shelf life through reduced chlorophyll degradation and nutrient loss [3, 45, 62, 63], highlighting the importance of optimizing cinnamon oil concentration for maximal quality retention.

Effect on Antioxidant Properties

The effect of Gum Arabic (GA), Keratin (K), and Cinnamon Oil (CO) coatings on the ferric reducing antioxidant power (FRAP) of stored tomatoes is presented in Fig. 4a. The reducing power of tomato juice from both treated and untreated groups ranged between 51.32% and 177.3%. A significant increase in FRAP values was observed up to day 15 across all treatment groups, while the control group

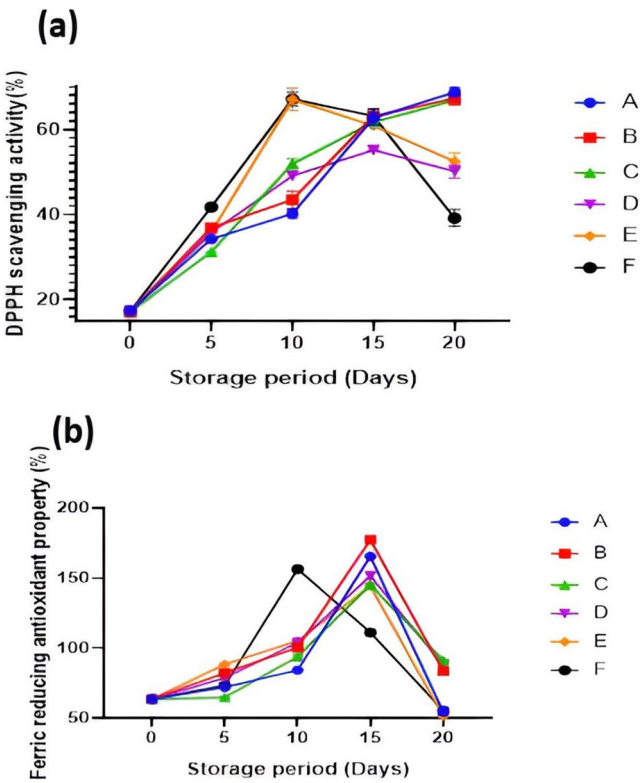

Fig. 4 Effect of Gum Arabic (GA), Keratin (K) and Cinnamon oil (CO) treatment on (**a**) FRAP, and (**b**) DPPH of stored tomato. Data are means ± SD of three determinations. Note: A, GA-K-$CO_{0.5}$ (27:3:0.5); B, GA-K-$CO_{0.1}$ (27:3:0.1); C, GA-K (27:3); D, GA (15% w/v); E, keratin (5% w/v); F = Control (distilled water). DPPH, 1,1-diphenyl-2-picrylhydrazyl; FRAP, ferric reducing antioxidant property

consistently exhibited the lowest values. However, by day 20, a decline in FRAP values was recorded in both the treated and control groups, suggesting that the gum Arabic-keratin-cinnamon oil coating may be effective in preserving antioxidant potential only up to 15 days but loses efficacy thereafter. The higher FRAP values observed in groups A and B on day 15 could be attributed to the synergistic effects of gum Arabic (antioxidant capacity), keratin (mechanical strength), and cinnamon oil (antimicrobial activity), which collectively enhanced the preservation of tomato fruit. These findings align with previous studies that have reported the role of gum Arabic and keratin coatings in reducing oxidative stress and maintaining antioxidant potential in fresh produce [19, 73, 93, 98]. Furthermore, a recent review by Khan et al. [42] highlighted that a triple-coating system applied to tomatoes and meat products exhibited superior antioxidant preservation compared to single-component coatings, further supporting the efficacy of multi-layered biopolymeric coatings for postharvest management.

The effects of the coatings on the 1,1-diphenyl-2-picrylhydrazyl (DPPH) radical scavenging activity of stored tomatoes is presented in Fig. 4b. The antiradical activity, as measured by DPPH scavenging capacity, ranged between 17.14% and 69.72% across the storage period. A significant increase in DPPH radical scavenging activity was observed as storage progressed, with group A exhibiting the highest activity by day 20, followed by groups C and D. These findings indicate that the combined application of gum Arabic, keratin, and cinnamon oil was more effective in preserving antioxidant activity than coatings formulated with gum Arabic or keratin alone. This study aligns with the findings of Taher et al. [87] who reported that gum Arabic-coated tomatoes exhibited enhanced DPPH scavenging ability, contributing to extended shelf life and improved retention of antioxidant capacity. Similarly, Eidangbe and Oluba [25] demonstrated that keratin-coated tomatoes maintained significantly higher DPPH radical scavenging activity compared to untreated tomatoes, further reinforcing the effectiveness of biopolymer-based coatings in postharvest preservation.

Microbiological Analysis

Sterility Assessment of the Coating Medium

The sterility evaluation of the coating medium, as presented in Fig. 5a, was conducted over 48 h to assess its suitability as a natural bio-preservative. The findings indicate that the coatings exhibit appreciable microbiological stability and sustained residual antimicrobial potency under ambient conditions. The coating medium showed inhibitory activity against bacterial and fungal proliferation by suppressing microbial populations below 100 CFU/mL throughout the study period [4, 61]. The results further reveal that the antibacterial effectiveness of the coatings was more pronounced than their antifungal efficacy. This observation is particularly relevant considering the rapid proliferation rate of bacteria compared to the longer incubation time required for most fungi, except yeast species. Among the tested formulations, GA-K-$CO_{0.5}$, GA-K-$CO_{0.1}$, keratin, and control exhibited superior sterility, suggesting their potential for enhancing the shelf life, quality, and safety of coated tomatoes. Notably, a contaminated coating medium would pose a risk of introducing spoilage organisms rather than preventing microbial deterioration. Therefore, the observed sterility reinforces the role of these coatings in preventing pathogen proliferation and ensuring food safety. These findings align with Cherop [14], who reported that while gum Arabic is not inherently sterile, it remains effective in prolonging the shelf life of food products through its antimicrobial properties.

Anti-inhibitory Effects of Coating Medium

The antimicrobial properties of the coating medium are presented in Fig. 5b. In addition to exhibiting notable stability, the antimicrobial effectiveness of the coatings was evaluated using standard antimicrobial susceptibility testing methods against two bacterial strains (*Escherichia coli* and *Staphylococcus aureus*) and two foodborne fungal contaminants (*Aspergillus flavus* and *Penicillium* spp.). The findings reveal that coating medium GA-K-$CO_{0.5}$ demonstrated broad-spectrum antimicrobial activity, exhibiting zones of inhibition measuring at least 13.0 mm (2r) against the tested opportunistic, toxigenic, and spoilage microorganisms [21, 24]. In contrast, coating media GA-K-$CO_{0.1}$, GA-K, GA, and keratin displayed relatively lower inhibitory efficacy, showing limited effectiveness against 0.5 MacFarland standardized bacterial inocula and 1.0×10^6 spores/mL of the test fungi. Among the tested microorganisms, *Staphylococcus aureus* was the most susceptible, exhibiting pronounced inhibition by all coating media except GA-K-$CO_{0.5}$. Conversely, *Penicillium spp*. demonstrated the highest resistance, with inhibition observed only in GA-K-$CO_{0.1}$. Overall, the results suggest that the coatings possess stronger antibacterial activity than antifungal properties. Under optimal conditions, the coating medium can serve as an effective preservative for agricultural produce, offering protection against bacterial and yeast contaminants while selectively inhibiting fungal growth.

Effect on Bacterial Load

The coating medium effectively reduced bacterial loads on tomatoes, starting from 5.1×10^4 CFU/g across all groups. Most treatments showed bacterial decline within the first

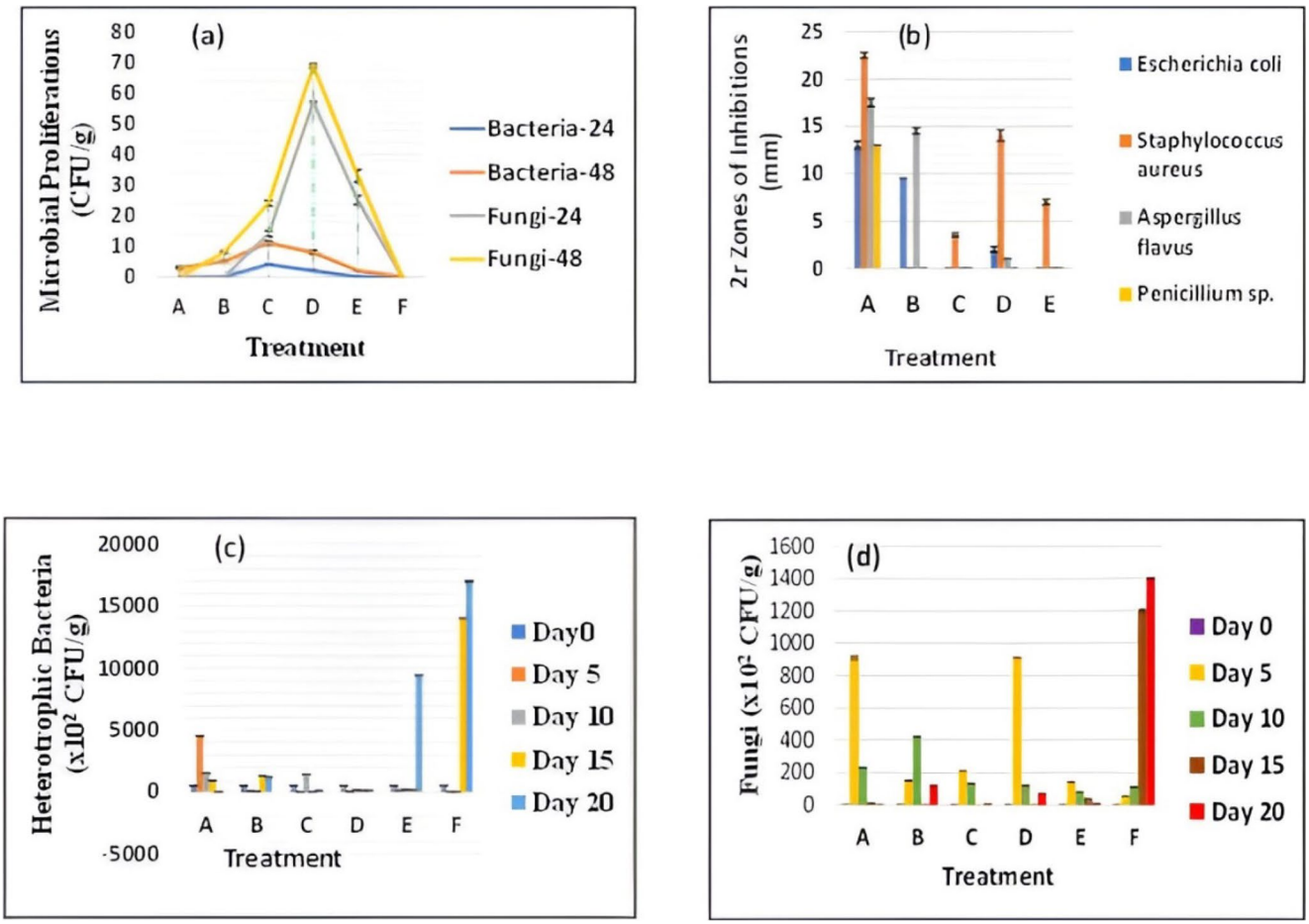

Fig. 5 (**a**) Sterility assessment of the coating medium, (**b**) anti-inhibitory effects of coating medium against the test organisms, (**c**) bacterial load dynamics in coated tomato fruits, and (**d**) fungal load dynamics in coated tomato fruits. Data are means ± SD of three determinations. Note: A, GA-K-$CO_{0.5}$ (27:3:0.5); B, GA-K-$CO_{0.1}$ (27:3:0.1); C, GA-K (27:3); D, GA (15% w/v); E, keratin (5% w/v); F= Control (distilled water)

five days, with GA-K-$CO_{0.1}$ maintaining reduction up to day 10 but losing efficacy by day 15, likely due to microbial adaptation. Fluctuations in bacterial populations in other groups suggest succession influenced by antimicrobial compound release and environmental factors. Keratin maintained antibacterial effects till day 15 before bacterial proliferation increased. Despite these dynamics, all coatings kept bacterial counts below the safety threshold of 1.5×10^5 CFU/g, supporting microbial safety during storage (Fig. 5c). These results align with prior findings of Sarengaowa et al. [76] and Venkatachalam et al. [92] on antimicrobial coatings in produce storage. The antibacterial effectiveness of the coating substance can be attributed primarily to cinnamaldehyde, the primary active constituent of cinnamon oil. Cinnamaldehyde's bactericidal effect arises from its disruption of bacterial cell membranes through interaction with the lipid bilayer, leading to increased membrane permeability and leakage of vital intracellular components, such as ions and ATP, ultimately impairing bacterial survival [23, 66]. Cinnamaldehyde's reactive aldehyde group allows it to form covalent bonds with bacterial enzymes and proteins through Schiff base and Michael addition reactions, effectively obstructing vital metabolic pathways and replication process [91]. This multi-targeted mode of action results in effective bacterial suppression, as confirmed by the observed reduction in bacterial CFU/g during storage. The gum Arabic-keratin composite serves as a protective structure, minimizing cinnamaldehyde loss through evaporation and degradation, which allows the coating to preserve its antimicrobial properties and release bioactive compounds in a controlled manner over time [77]. Keratin enhances the mechanical integrity and cohesiveness of the film through disulfide and hydrogen bonding, providing stability and prolonged antimicrobial efficacy [60]. Despite initial bacterial suppression, fluctuations and increases in bacterial populations after extended storage may stem from microbial adaptation, environmental contamination, or the depletion of active antimicrobial compounds.

Effect on Fungal Load

The coating medium demonstrated significant antifungal efficacy on tomatoes. Initial fungal load (2.2×10^2 CFU/g) sharply increased within 5 days due to mold adaptation. Treatments with cinnamon-enriched coatings (GA-K-$CO_{0.1}$, GA-K-$CO_{0.5}$) and others achieved over 40% fungal reduction by day 10 and sustained suppression through day 20, keeping fungal levels below 1.5×10^4 CFU/g. The control failed to maintain inhibition while GA-K-$CO_{0.1}$ was most effective, highlighting its promise for sustainable tomato preservation (Fig. 5d). Similar to bacterial targets, cinnamaldehyde, the major bioactive component of cinnamon, disrupts the integrity of fungal cell membranes, causing structural disintegration and leakage of intracellular contents [36, 23]. The antioxidant properties of cinnamaldehyde also mitigate oxidative stress in fruit tissue, thereby preserving host defenses and indirectly limiting fungal colonization. The gum Arabic-keratin matrix synergistically contributes by forming a semi-permeable barrier that modulates moisture loss and limits germination and growth of fungal spores [73]. Progressive reductions in fungal counts indicate a cumulative inhibitory effect likely resulting from sustained release of bioactives and the durability of the film. Coumarin, a component of cinnamon oil that is also bioactive, enhances antifungal efficacy due to its known preservative properties [97]. As a result, the complex composition of the coating enables it to effectively delay fungal spoilage throughout the storage period.

Effect on Sensory Attributes

Data presented in Table 2 reveal that tomatoes treated with a composite film made from gum Arabic, keratin, and cinnamon oil exhibited notably better sensory ratings, encompassing aroma, appearance, color, texture, and overall preference, when compared to untreated control samples. Notably, treatments containing cinnamon oil (GA-K-$CO_{0.5}$) achieved the highest ratings for all attributes, reflecting enhanced physicochemical and sensory qualities. The observed improvements in the physicochemical, nutritional, and microbial stability of tomatoes coated with the gum Arabic-based composite could be attributed to several formulation features. Gum Arabic forms a semipermeable barrier, reducing moisture loss and delaying ripening, which helps maintain firmness and color. Keratin strengthens the coating matrix by providing structural rigidity, improving mechanical protection against physical damage, and enabling enzymatic softening [61]. Cinnamaldehyde-rich cinnamon oil exhibits potent antimicrobial activity by disrupting microbial membranes, directly reducing bacterial and fungal loads [23, 66]. These mechanisms work synergistically to preserve sensory attributes, limit nutrient loss, and prolong shelf life, supporting the composite's value in sustainable postharvest management.

Readings show mean of 20 panelist members on 9-pont hedonic scale where 9 indicate like extremely and 1 indicates dislike extremely. Note: A, GA-K-$CO_{0.5}$ (27:3:0.5); B, GA-K-$CO_{0.1}$ (27:3:0.1); C, GA-K (27:3); D, GA (15% w/v); E, keratin (5% w/v); F = Control (distilled water).

GC-MS Analysis of Cinnamon Oil

The GC-MS fingerprint of cinnamon oil (Fig. 6) in this study revealed a chemically diverse profile that aligns broadly with previously reported findings. However, variations were observed in the number and relative abundance of volatile aldehydes when compared to earlier studies [10, 97]. These discrepancies may be attributed to differences in cinnamon cultivars, geographic origin, and environmental or agronomic conditions influencing phytochemical composition. The GC-MS analysis identified cinnamaldehyde (38.9%) and coumarin (3.05%) as the predominant bioactive compounds in the cinnamon oil (Table 3), playing significant roles in the coating's effectiveness. Cinnamaldehyde is well-documented for its broad-spectrum antimicrobial properties, primarily by disrupting microbial membranes and inhibiting the functioning of key enzymes, which corresponds with the substantial decreases in both bacterial and fungal loads reported in tomatoes treated with cinnamon oil-infused gum Arabic-keratin coating [23, 66]. Its antioxidant properties likely contribute to improved oxidative stability and nutritional quality preservation. Coumarin complements this by offering antifungal and preservative effects, enhancing the coating's ability to suppress spoilage

Table 2 Effect of GAKO on the sensory attributes of matured green tomato (*Solanum lycopersicum* L.) after storage

Sample	Aroma	Appearance	Color	Firmness	Overall acceptance
A	5.9 ± 0.52^{ab}	5.9 ± 0.28^{b}	5.65 ± 0.33^{ab}	5.85 ± 0.22^{bc}	6.25 ± 0.22^{b}
B	6.8 ± 0.55^{b}	7.5 ± 0.30^{c}	7.8 ± 0.35^{c}	7.61 ± 0.18^{d}	7.90 ± 0.16^{c}
C	5.5 ± 0.52^{ab}	5.6 ± 0.22^{b}	6.05 ± 0.28^{ab}	5.95 ± 0.30^{c}	6.30 ± 0.21^{b}
D	4.8 ± 0.51^{a}	4.75 ± 0.28a	5.35 ± 0.31^{ab}	4.95 ± 0.32^{a}	5.30 ± 0.25^{a}
E	5.3 ± 0.52^{ab}	5.25 ± 0.24^{ab}	5.21 ± 0.27^{ab}	5.00 ± 0.29^{a}	5.30 ± 0.27^{a}
F	6.1 ± 0.55^{ab}	5.40 ± 0.34^{ab}	5.05 ± 0.37^{a}	5.00 ± 0.36^{ab}	5.70 ± 0.29^{ab}

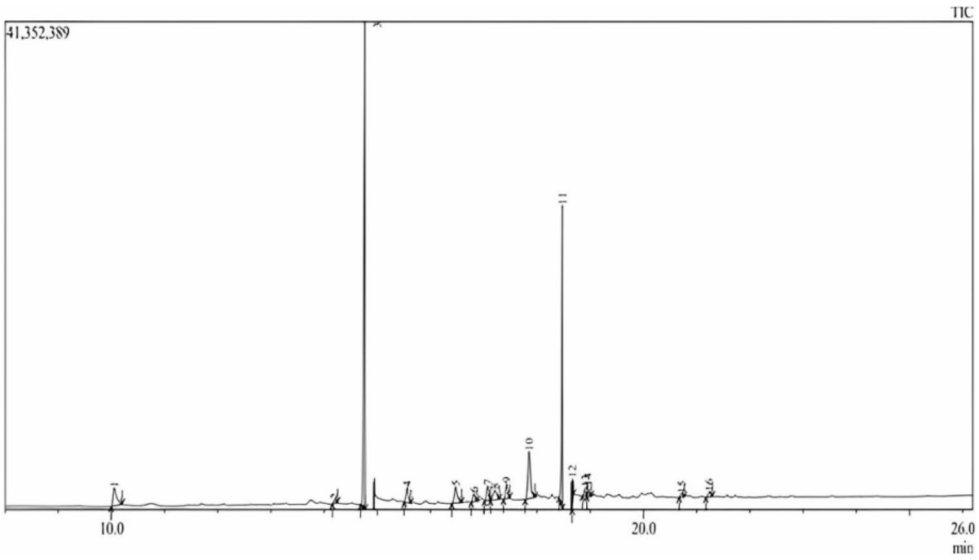

Fig. 6 GC-MS fingerprint of cinnamon oil

Table 3 Bioactive components of cinnamon oil identified by GC-MS analysis

S/*N*	Compound	Abundance
1	Benzaldehyde	5.72
2	Benzaldehyde, 2-methoxy-	0.66
3	Cinnamaldehyde,	38.9
4	Acetic acid, cinnamyl ester	3.16
5	.gamma.-Muurolene	1.63
6	alpha.-Muurolene	2.71
7	Coumarin	3.05
8	Naphthalene, 1,2,3,4-tetrahydro-1,6-dimethyl-4	2.87
9	2-Propenal, 3-(2-methoxyphenyl)-	11.25
10	Spiro[androst-5-ene-17,1'-cyclobutan]−2'-	1.32
11	.alfa.-Copaene	1.79
12	alpha.-Cadinol	1.61

molds and extend shelf life [97]. The sustained release of these compounds from the gum Arabic-keratin matrix ensures prolonged microbial resistance and quality retention, thereby validating the composite coating as a potent natural postharvest preservative. It was also observed that higher concentrations of cinnamon oil in coatings may accelerate carotenoid degradation in tomatoes due to increased presence of reactive aldehydes, chiefly cinnamaldehyde. These aldehydes promote oxidative reactions and enhance the breakdown of heat- and light-sensitive carotenoids such as β-carotene and lycopene. Some studies have also shown that high essential oil levels may disrupt cellular membranes and alter antioxidant balance, making carotenoids more susceptible to oxidative loss during storage [2, 16, 83]. Thus, while cinnamon oil improves microbial stability, its higher doses can chemically destabilize key nutrients in tomato tissues, necessitating a balanced formulation for optimal quality retention.

Conclusion

This study demonstrates the potential of the biodegradable gum Arabic-keratin-cinnamon oil (GA-K-CO) composite as an effective postharvest treatment to enhance tomato quality and storage stability under ambient conditions. The bioactive constituents of the cinnamon oil infused-gum Arabic-keratin composite coating, particularly cinnamaldehyde, provide microbial protection by disrupting microbial membranes and inhibiting spoilage. However, a trade-off emerges as higher cinnamon oil concentrations accelerate the degradation of sensitive carotenoids such as β-carotene and lycopene, through oxidative pathways involving reactive aldehydes. Future research should explore encapsulation or nano-delivery systems to control the release of cinnamon oil volatiles, minimizing carotenoid oxidation while sustaining antimicrobial efficacy, to reconcile microbial protection with nutrient preservation. Further studies on extended storage durations and varying environmental conditions are warranted. Overall, the GA-KO coating offers a promising sustainable alternative for enhancing shelf life, especially in regions lacking cold-chain infrastructure.

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Author Contributions **Titilope A. Fashanu** : Conceptualization, Methodology, Data acquisition, Data analysis, Writing – Original draft. **Charles O. Nwonuma: ** Conceptualization, Methodology, Data acquisition, Supervision. Writing – Original draft. **Olarewaju M. Oluba** : Conceptualization, Methodology, Data analysis and visualization, Supervision, Writing – review & editing.

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Data Availability All data generated or analyzed during this study are included in the manuscript.

Declarations

Ethics Approval and Consent to Participate The study was approved by the department of Biochemistry, Landmark University, Omu-Aran, Nigeria, as part of our efforts to promote responsible production and consumption within the agro value chain.

Compliance with Ethical Standards The plant material used in this study, tomato fruits, were obtained from a local tomato farmer in Ilorin, Kwara State, Nigeria. The collection and use of the tomato samples complied with all relevant local and national agricultural and research guidelines. No endangered or protected plant species were involved, and no permissions or licenses were required for their collection and use.

Consent to Participate Not applicable.

Consent for Publication All co-authors consented to the publication.

Competing interests The authors declare no competing interests.

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